NASA Strategic Framework for On-Demand Air Mobility

Part 2: Alignments Between ODM and UAS Airspace Management Needs and Contributions from Current R&D Activities and Plans

A Report for NASA Headquarters
Aeronautics Research Mission Directorate

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EXECUTIVE SUMMARY

The Aeronautics Research Mission Directorate (ARMD), NASA Headquarters, requested a high-level assessment of the adequacy, completeness and relevance of current investments in UAS airspace management technology development projects for meeting the unique needs of On-Demand Mobility (ODM) airspace operations. Two domains of ODM are considered, one for urban VTOL operations, a second for inter-urban Conventional Take-Off and Landing (CTOL) or Vertical Take-Off and Landing (VTOL) operations. Among other documents, two sets of NASA Unmanned Aerial Systems (UAS) project planning documents were reviewed, one for the UTM (UAS ATM) and a second one for the UAS National Air Space (NAS) integration projects. The preparation of strategic context for this study included numerous other reports and related UAS activities; further, this present (Part 2) study builds on an earlier study: “NASA Strategic Framework for On-Demand Mobility,” delivered to NASA in January 2017.

The study team defined ODM as a distribution environment that optimizes purpose of movement, exploiting appropriate technologies, operational capabilities and other variables to assure safe and efficient transit on and above the surface for the movement of people and packages. The team reached the following distilled conclusions, findings and recommendations:

Strategic Context

• The challenges to making changes that enable ODM in the current NAS are daunting, but key enabling technologies are in hand.
• Now is the time for bold action to respond to the opportunities of UAS and ODM

Alignments and Gaps

• Current NASA and FAA plans for UAS airspace operating capabilities and enabling technologies will contribute to, but will not adequately provide for the needs of the emerging ODM architecture, vehicle and ATM concepts.
• ODM concepts require certain autonomy and automation capabilities not envisioned in current NASA and FAA technology planning.

Recommendations

• Lead:
  - Transition today’s human operator and controller-centric system of air traffic management and control to an integrated, vehicle-centric system that enables the movement of all vehicles including UAS, ODM and conventional aircraft.
  - Create an X-NAS (Experimental National Airspace System test environment) in which X-Plane-based / ODM vehicles, ATM concepts, and related safety system solutions can be evaluated in simulation as well as real-world environments.
• Collaborate: Promote investments in public transportation data, for advancing modal demand forecasting, evaluating relevant technologies, and conducting consumer acceptance studies.
• Follow: Partner with FAA, industry and academia to develop requirements, technologies and systems required to adapt and then transform the existing NAS to fully enable UAS and ODM systems innovations.
CHAPTER 1 - INTRODUCTION AND STRATEGIC CONTEXT

Introduction

The global aeronautics enterprise stands at the threshold of a transformative epoch in the role of aviation for the movement of people, goods and ideas throughout increasingly pervasive origins and destinations in a broader spectrum of vehicle types, utilizing more airspace. Enabling technologies are emerging and converging to create the “push” for the envisioned advancements in vehicle and airspace systems. The need for advances in safe, affordable, clean, distributed and efficient mobility in the air as well as on the ground create the “pull” for the envisioned transportation capabilities and services. This transformation has significant implications for airspace management and related policy, regulatory, equipage and infrastructure considerations.

This report follows on from an earlier study on “A Strategic Framework for On-Demand Mobility (ODM),” completed for NASA in January 2017. That study provided an analysis of the strategic framework and public value proposition for ODM vision and concepts, to help inform NASA’s technology investment portfolio, its planning and its advocacy. The current report addresses a topic not covered in the first report: Air Traffic Management strategies for ODM. Both the first and this (Part 2) report provide a high-level strategic view from a team of subject matter experts experienced in all aspects of aviation innovation: aircraft, airspace, airports, operations, policy, regulation, technology, strategy, partnerships and finance.

Strategic Context

The prior study highlighted a key element of the public value proposition for ODM as motivated by the vital role of connectivity between supply and demand among markets, as it affects productivity in the national economy. Further, the study drew on recent analyses of the decline in American productivity over the decades since the 1970’s. The report also offered the hypothesis for public value of ODM technology investments by NASA, that such investments would play a role in improving markets connectivity, thus mitigating the decline in productivity, with attendant public benefits in quality of life, economic opportunity and standard of living.

Our team has been asked by NASA Headquarters to assess the adequacy, completeness, and relevance of current investments in UAS airspace management technologies for meeting the unique needs of the On-Demand Mobility (ODM) system requirements.

For purposes of this paper, the Study Team defined ODM as a distribution environment for people and packages optimized for purpose of movement, exploiting appropriate technologies, operational capabilities and other variables to assure safe and efficient transit on and above the surface for the movement of people and packages. For vehicles that can meet designated

1 http://www.nianet.org/ODM/roadmap.htm
2 https://www.wsj.com/articles/the-economys-hidden-problem-were-out-of-big-ideas-1481042066
“measures of success” of the ODM architecture, full system benefits can be achieved. Other participating and nonparticipating vehicles may be accommodated, though constrained by having to meet residual legacy or sub-optimal operational requirements.

The spectrum of ODM vehicle concepts under development by industry include: 1. Intra-urban VTOL (in models envisioned, for example by Aurora Flight Sciences and Uber Elevate\(^3\)); 2. Inter-urban VTOL and CTOL (in air taxi or thin-haul models envisioned, for example, by Lilium\(^4\) or Zunum Aero\(^5\)). This report summarizes the findings and recommendations as a result of our review of the current NASA UAS and airspace management-related projects and their contributions to and alignment with the needs of planned ODM concepts.

The two NASA technology projects underway related to operations of different classes of UAS in the National Airspace System include the following:

1. UAS Air Traffic Management Project: UTM Project
2. Full UAS Integration Framework Team: “UAS in the NAS” Project

The team reviewed project documentation listed below, and many other documents (see Appendix A), related to management of airspace involving UAS operations. The principal reference materials reviewed for this study are listed here:


This report is organized in an Executive Summary plus five chapters and an Appendix, as follows:

Executive Summary

\(^3\) https://www.uber.com/elevate.pdf
\(^4\) https://lilium.com
\(^5\) http://zunum.aero
1. Introduction and Strategic Context
2. A Unified ODM Airspace Management Concept Description
3. ODM Concept, Demand and Airspace Loading Considerations
4. NASA UAS Projects and Outcome Alignments with ODM Needs
5. Conclusions, Summary, and Recommendations
Appendix A: UAS Literature Summary
Appendix B: An Assessment of ODM Demand Estimation

Summary
This report provides a high-level assessment of our team’s view of the airspace management requirements that would stimulate the rate of emergence of ODM aircraft and related transportation services in the U.S. We also assess the adequacy of the current NASA UAS airspace management research, as reported in project planning and progress materials, to satisfy the ODM requirements. Finally, we address issues related to policy, regulation and certification that require attention for the ODM visions and concepts to flourish, and to inform development of an advanced architecture that facilitates the efficient movement of people and packages between more widely distributed origins and destinations.

Findings and Recommendations
Following is a series of findings and recommendations of this chapter, which are developed in greater detail in the chapters that follow:

Finding 1.1 – The recent emergence of industrial initiatives in ODM vehicle developments have not been matched by FAA and NASA initiatives in airspace management that would be required to support intended operations of large numbers of the new kinds of aircraft in commercial or private service.

Finding 1.2 – The emergence of the UAS (or drone) industrial initiatives for vehicle concepts, mission concepts and airspace management concepts provides sources of technology advancements in propulsion, control, manufacturing, communication, navigation, surveillance and related airspace management concepts of relevance to the ODM visions and concepts.

Finding 1.3 – The airspace management concepts being evaluated for UAS operations in the two referenced NASA projects do not satisfy the needs for ODM operations for either the urban and inter-urban vehicle and mission concepts.

Finding 1.4 – Current regulatory structures are inadequate to encourage or support the pace of innovation and the introduction of an ODM distribution system to match industrial timelines.
CHAPTER 2 – A “UNIFIED” AIRSPACE MANAGEMENT CONCEPT

Introduction

The quickened pace of business and the public’s growing impatience with sluggish movement of people and materials have increased the demand for greater mobility. Market opportunities, innovation and advanced technologies provide a significant incentive to develop a new architecture for the management and flow of vehicles regardless of mode. This chapter summarizes the study team’s evaluation, findings and recommendations regarding requirements for distribution system management, with a focus on the airspace aspects.

Movement of People and Packages: While smartphones and high-speed Internet have expanded connectivity (which intuitively might suggest a reduced need to travel), passenger counts on scheduled airlines continue to grow even as the number of city pairs with nonstop service has diminished. The cost of scheduled airline service for flights of less than 500 miles has increased, as has the time needed to transit from initial departure to ultimate destination over typical travel distances.

Service provided by Scheduled Airlines operating under Part 121 of the Federal Air Regulations (FAR) and by operators of chartered aircraft under FAR Part 135 illustrate the inability or reluctance of today’s air carriers to satisfy the public’s travel expectations. The mobility they offer is characterized by inconvenient schedules between limited city pairs (and no direct flights between most smaller communities), time wasted, high per-mile costs and intermodal limitations. Today’s aircraft must operate between airports or heliports and thus require a second vehicle mode to complete a travel mission.

A recent study—of which this paper is Part 2, NASA Strategic Framework for On-Demand Mobility—postulated that significant benefits would result from enabling anyone to fly anywhere, anytime for productivity and pleasure. The report envisioned vehicles capable of vertical takeoff and landing as well as autonomous operation. Innovative VTOL vehicles employing electric propulsion and fan-in-body concepts, supported by advanced flow management and autonomous control systems, could enable an On-Demand Mobility (ODM) system that would significantly improve the movement of people and packages.

Consumers are visiting retail stores less frequently, choosing instead to shop via e-commerce and using Internet-related delivery services. They perceive the Internet as providing the latest information on the newest models, and they value time saved and new convenience enjoyed by not traveling to a mall or outlet store. Goods ordered online are expected to arrive the next day (or possibly sooner) and consumers may demand that “return” services be equally responsive, thus driving significant increases in the commerce of goods and packages. Companies that have embraced e-commerce and provide rapid delivery of orders enjoy significant growth. Quick and efficient distribution and delivery have become competitive advantages.

Similarly, consumers of air travel have expressed frustration with available services. Limited access to direct, non-stop flights between city pairs, scheduling delays, security considerations and congestion combine to discourage air travelers, whether they fly for business or pleasure.
Thus, it is reasonable to postulate that the public’s demand for increased mobility would
provoke architectures to optimize the movement (i.e., distribution) of people and packages. Benefits in efficiency, productivity and improved quality of life accruing from such an advanced movement system clearly warrant adequate investments in research and development.

**Satisfying Expectations:** Broad interest in greater mobility is reflected in the aspirations of advanced tech companies such as Amazon, Google, Lyft, Tesla and Uber to develop and employ autonomous vehicles. Each of these firms is actively pursuing driverless vehicles, and Uber outlined a program of autonomous air transportation in its paper entitled *Elevate*.\(^6\) Volvo, BMW, Ford and other traditional automobile manufacturers are rapidly embracing the possibility of autonomous cars. In its July 19, 2017 publication, *The Motley Fool* reported that 44 corporations including automakers and Tier-1 part suppliers (but not start-up companies) were actively exploring market opportunities related to self-driving cars.

**Unmanned Aerial Systems:** In addition to interest in greater mobility, demand for Unmanned Aerial Systems (UAS) has exploded. The May/June 2017 issue of *FAA Safety Briefings* stated that there are more than 750,000 registrations for unmanned aircraft as of the issue’s publication date, nearly 3.6 times the number of manned aircraft listed. Sales of drones are expected to exceed one million during 2017. While many Unmanned Aerial Systems are currently owned by hobbyists and will be used solely for recreational purposes, a recent study\(^7\) by Doctors Darryl Jenkins, Bijan Vasign and Tulinda Larson and by Professor Clint Oster states that “UAS is a disruptive technology… [representing] a new way of doing things that [will] disrupt or overturn traditional business models and practices.” Of the more than 1,000,000 small UAS that were registered in the USA during the first 18 months of the FAA’s required program of documentation, roughly 100,000 were for commercial purposes, according to the Jenkins, et al paper. The FAA forecasts that the commercial UAS fleet in the United States will grow to 500,000 by 2021.

Jenkins, et al postulate that within 20 years aerial deliveries of packages via UAS will range from 8 million to 86 million operations per day! According to their analysis, the annual economic savings to logistics companies will be at least $2 billion (based upon a pessimistic forecast of 8 million daily movements) to $10 billion (based on nominally 50 million daily operations).

Thus, an architecture that enables greater mobility must address the needs of the rapidly growing UAS community as well as adopters of ODM concepts. To be efficient and universally accepted, however, an advanced system of vehicle management and safety must also include a feasible means of transitioning from legacy operations and regulatory structures to a unified system where all users embrace the advantages of equipage to the proposed architecture.

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\(^6\) [https/www.uber.com/info/elevate/](https://www.uber.com/info/elevate/)

\(^7\) Jenkins, Darryl, and Bijan Vasign. The economic impact of unmanned aircraft systems integration in the United States. Association for Unmanned Vehicle Systems International (AUVSI), 2013
Furthermore, integrating UAS and ODM distribution and management solutions with the needs of legacy entities provides the motivation and opportunity to address, solve and demand new approaches for long standing legacy challenges in aviation, such as autonomous operation, route optimization, traffic sequencing, separation self-negotiation, collision protection, terrain clearance and obstacle avoidance. The range of new operational and performance capabilities of UAS and ODM vehicles (including vertical take-off and landing, highly maneuverable flight, variable speeds from hover to near supersonic, loitering, and multi-modal operations on the earth’s surface, in the air or on water) will provide new dimensions of mobility, productivity and economic value, thus demanding a new paradigm of organization and regulatory structure.

Managing Diverse Interests and Needs: A sign that management concepts for UAS will shape air traffic management and control (ATM/ATC) architectures is reflected in the growing trend among local communities to enact their own ordinances and procedures for regulating UAV/UAS/drones. Helicopter Association International (HAI) President Matt Zuccaro told a panel at the 2017 Business Aviation Conference held by the National Air Transportation Association (NATA) June 6th through June 8th that “…there are currently in excess of 1,000 local ordinances, rule and regulations regarding drone operations, and drones are a category of aircraft.” Zuccaro mused that individual communities might perceive the lack of a unified management of airspace by the federal government as a tacit license to devise individual systems of ATM/ATC for unmanned aerial vehicles, and by extension manned vehicles. “There’s nobody challenging them,” he said, noting that helicopters and drones have similar flight profiles and suggesting that local communities might extend their interests in airspace management to locally operated helicopters.

Many companies, some well-established and experienced in the arena of Air Traffic Management and Control, as well as others with significant resources but less involvement in ATM/ATC, are exploring how they might participate in the integration of UAS and traditional aircraft. An advanced architecture that integrates (i.e., unifies) our nation’s movement and distribution of vehicles will enable new technologies such as UAS and ODM to develop while also providing a path for legacy systems to participate in projected market opportunities.

Equality important is the need to avoid inhibiting the development of an advanced architecture by imposing constraints from the current ATM/ATC system, including NextGen, on the development of domain management for the safe, efficient and productive movement of vehicles.

Today’s architects, managers and users of the U.S. National Airspace System must address how future vehicles as well as legacy aircraft can be operated safely and productively as elements within an integrated distribution system. Designing and implementing such architecture, which for identification we call Integrated Advanced Mobility System (IAMS), will enable realization of economic and quality-of-life benefits derived from efficient movement of people and packages.

**ODM Airspace Management Objectives and Measures of Success**

This section proposes an architecture to enable the safe and efficient distribution of objects transiting airspace, whether that vehicle is manned, unmanned or remotely operated, and whether autonomous or semi-autonomous. Our team’s analysis of the Reno UTM experiment and the Team of Experts report, which are discussed in detail within Chapter 4 (NASA
UTM/UAS Projects and Outcome Alignments with ODM Needs), provides much of the motivation for the definition of this architecture.

The imagined system accommodates legacy operations and depends on their being attracted by ODM system safety, efficiency and other benefits to transition from being “accommodated” to full adoption of new equipage and performance, and participation in the vehicle-centric architecture identified below as IAMS (Integrated Advanced Mobility System). An additional benefit of the proposed methodology is its applicability to the safe, efficient and productive accommodation of emerging vehicles capable of providing surface and airborne distribution services within an IAMS architecture.

The Measures of Success (MoS) presented below are Governing Principles of the proposed Integrated Advanced Mobility System (IAMS):

- The probability of a collision between vehicles operating within the architecture’s domain is less than $10^{-9}$.
- A probability of a collision between vehicles and terrain while operating within the architecture’s domain less than $10^{-9}$.
- The probability of loss of control due to weather while operating within the architecture’s domain is less than $10^{-9}$.
- The probability of loss of control due to data interference or interruption of control guidance while operating within the architecture’s domain is less than $10^{-9}$.
- Emergency deviations to a safe termination can be accommodated immediately.
- Transit time penalty to achieve the IAMS’ Measures of Success (i.e., Governing Principles) for vehicles operating within the IAMS domain is no more than five percent greater than moving directly from departure point to destination based upon the operator’s desired performance for the vehicle.
- Access to IAMS generally will be immediate, but delays at no time will exceed 10 minutes.
- The IAMS architecture can accommodate safe movement of any vehicle capable of operation in accordance with system requirements, regardless of mode, and can facilitate optimum movement of appropriately equipped vehicles.
- Vehicles that are fully compliant with IAMS equipage and performance capabilities will derive optimized purpose of movement. Others will be accommodated, but may not realize full optimization.
- Unless specifically excluded from the Integrated Advanced Mobility System domain, all airspace from ground level through Flight Level 600 would be subject to the Measures of Success outlined above and all vehicles would conform to IAMS requirements.

In addition to the above quantitative measures of success, the following qualitative measures are also proposed:

- IAMS architecture is scalable to allow a smooth transition from today’s human-operator/controller centric Air Traffic Management and Control to an autonomous, vehicle-centric, interactive separation, avoidance and sequencing system.
- The IAMS architecture enables optimization of a wide range of transit purposes, routes, destinations, speeds, altitudes, loitering and other movement characteristics.
- The architecture is not “brittle” (i.e. the system remains stable under stress).
• The architecture is resilient to perturbations such as weather, to changing demands on the system, and to changing availability of system resources.
• The system architecture is resilient to alternative future “worlds”.
• The system architecture does not have any undesirable emergent properties.
• The system components that involve AI and machine learning behave as expected.
• The human/automation interaction design conforms to human factors principles.

The IAMS architecture enables optimization of a wide range of transit purposes, routes, destinations, speeds, altitudes, loitering and other movement characteristics.

Proposed Path, Separation and Management Methodology

Notionally, the Integrated Advanced Mobility System (IAMS) of Air Traffic Management and Control enables all vehicles to transit airspace in accordance with the Measures of Success (MoS) outlined above. Each participating vehicle will communicate its intentions and its progress along the intended path to all other relevant vehicles within the domain and with requisite ground data, information, and knowledge management facilities.

• Conflicts would be identified and resolved between vehicles with only minimal human operator or ground monitoring or intervention.
• Paths that satisfy the IAMS’s MoS would be calculated and continuously updated.
• The system will accommodate all participants (e.g., UAS, ODM and conventional aircraft), though penalties in time, route and convenience may accrue to vehicles with equipage or performance limitations.

IAMS-equipped vehicles would be capable of autonomous operations and be able to negotiate domain access, routing, traffic sequencing and traffic avoidance, and will avoid transponder-only equipped vehicles. Architecture for the IAMS enables access to all systems information needed for process monitoring, safe operations and purpose optimization. All vehicles enter, transit and exit IAMS domains in accordance with the Measure of Success outlined above.

Using position and ranging techniques such as Global Positioning Systems, vehicles capable of movement within the IAMS negotiate and constantly update destination and routing (the vehicle’s system knows its departure point). Onboard equipment gathers all available information, including data from vehicles within the sphere of possible conflict around the intended vehicle and along its apparent path, and calculates insertion and movement times and routing consistent with the IAMS’s Measures of Success. The system is self-contained—no human controller is involved. Intent data, which are updated continuously, are either loaded directly into the vehicle’s Flight Management System for autonomous operations or provided graphically to the vehicle’s pilot/occupant.

The number of vehicles that could be accommodated within the IAMS would be determined by several factors, including:

• Data transmitted and received from participating vehicles
• Time (latency) required to receive and process avoidance data from participating vehicles
• Accuracy of vehicle location as a function of time
• Predictability of vehicle location along its anticipated path.
• Operational capability (speed, altitude, maneuverability, etc.) of vehicles within the relevant region of influence. Note: The relevant region of influence is defined as the sphere around a vehicle where the Measures of Success can be achieved only by active cooperation between vehicles.

**Data Transmitted and Received:** Except during a transition period when special provisions for operating within proscribed vertical and horizontal boundaries will be allowed, each vehicle weighing more than a given weight (e.g., 55 pounds) operating in IAMS airspace would be equipped with at least a Mode C transponder. Additionally, for operation in proscribed sectors of IAMS airspace during the transition period, small Unmanned Aerial Systems without Mode C transponders must be equipped with a Sense-and-Avoid capability. At the end of the transition period, all vehicles would be able to compute, send and receive avoidance information, and vehicles not so equipped might be permitted within the IAMS but would have operational restrictions.

The character of the data sent between vehicles will impact the time required to generate resolutions or flight paths that satisfy IAMS requirements. Vehicles capable of simultaneous negotiated avoidance information (including altitude, position, direction, velocity and intent) will resolve conflicts faster than aircraft that receive only partial avoidance information, or only Mode C. IAMS equipped vehicles receiving only Mode C data will be required to compute the path of the transmitting vehicle and use the derived information to determine a flight path that satisfies IAMS Measures of Success.

The density of vehicles that could be accommodated within the IAMS would be affected by bandwidth, computational capability and processor speed of onboard data sensors. While processing data from vehicles that transmit only Mode C data would slow conflict resolution, the ability to identify all Mode C traffic enables a clear initial segregation of legacy-equipped vehicles and eventually enables an orderly transition from the existing ATM/ATC to the IAMS.

**Accuracy of Vehicle Location:** Being able to know, predict and avoid a vehicle’s position and to know or predict its intent (including path) determines the capacity of the Integrated Advanced Mobility System. The number of vehicles that the IAMS could accommodate depends upon the size of the sphere of space that must be protected to assure that vehicle location provides separation, as well as the mix of participating and non-participating (legacy) vehicles. The size and shape of the sphere is also dependent on the relative velocities and speed variability capability of the negotiating vehicles. (Mode C-equipped vehicles likely would have a larger sphere in dense traffic areas). Density may provoke operating limitations, such as imposition of defined routes, speeds or assigned altitudes.

**Technology Gaps, Simulation Needs, Demonstration and Contrarian Positions**

**Technology Gaps and Simulation:** The proposed Integrated Advanced Mobility System assumes the readiness of quick-response position sensors, high-speed processors, robust Internet protocol-based data communication networks, and direct feed between computed flight paths and a vehicle’s Flight Management System—all available at price points within the economic expectations of anticipated users of such a system.

Availability of real-time data and applications of artificial intelligence could enhance IAMS effectiveness by dynamically updating and recalibrating system performance. Machine
learning would likely enable vehicles operating within the IAMS environment to compensate for unusual traffic or weather situations.

While each element outlined for the IAMS exists, research questions must be addressed, such as:

- Is the level of technology readiness sufficient to support the vision of IAMS within a reasonable timeframe to be responsive to commercial and societal needs?
- Is the capability of sensors needed to implement the proposed Integrated Advanced Mobility System sufficient to satisfy the Measures of Success identified for the IAMS?
- Could the required sensors be obtained at price points that result in an economically viable IAMS?
- Considering the desired Measures of Success and the performance of each system component, how should vehicle density constraints within the Integrated Advanced Mobility System be determined?
- What is the sensitivity of factors affecting safety within the IAMS?
- What would a rigorous safety analysis show as potential weaknesses within the IAMS?
- What variables have the greatest impact on IAMS Measure of Success, at what level of flights within the IAMS does the system become unstable, what is the character of such instability and how could the system be managed to prevent such an occurrence?
- What will be the role and impact of emerging UAV/UAS participation in the Integrated Advanced Mobility System? (Are UAV/UAS inherently ODM? Will reliance on segmented airspace slow emergence of, or transition to a unified system.)
- What is a realistic time for transition between today’s ATM/ATC system and the proposed IAMS for all vehicle movements?
- The IAMS architecture proposes onboard computation of avoidance and path data. Would it be more efficient, cost effective and/or risk adverse if the computations were done by a centralized system and data linked to vehicles operating with the system?
- What are the estimated costs and savings attributable to an IAMS architecture versus the current ATM/ATC?
- Is there political will to transition from a pilot/controller centric architecture to one that is autonomous/vehicle centric?

Simulation is needed to address the questions above and to identify/quantify the risks/costs/benefits of the proposed IAMS architecture.

**ODM Concept Demonstration:** The proposed Integrated Advanced Mobility System is sufficiently encompassing and transforming to warrant thorough vetting. While simulation will be informative, a demonstration program best described as an X-NAS (Experimental National Airspace System) that employs experimental vehicles will be needed. Such an effort will require a dedicated test area, eventually expanding to examine real-world scenarios along the lines of the Capstone Project of the early 2000s that informed the benefits of ADS-B. Participation by all relevant stakeholders, including FAA, the Department of Defense and representative user group would be sought.
Consensus will be needed. Hence the requirement for a robust demonstration program following comprehensive analysis and simulation.

**Contrarian Positions**: Considerable effort, funding and time has been invested in the current National Airspace System and its management and control. Arguments could be made that architects for the US National Airspace System should “stay-the-course” and focus only on the system called NextGen. That approach, however, risks missing greater efficiencies and productivity in the distribution of people and packages offered by advanced technologies, innovation and the emergence of autonomous, UAV/UAS vehicles. Furthermore, the “stay-the-course” approach forces UAS and ODM vehicles either to be NextGen compliant (arguably impractical for UAS and inefficient for ODM) or be incorporated into an independent system divorced from NextGen.

The proposed IAMS focuses on developing a single "unified” system that addresses the needs of UAS and ODM while protecting users of legacy aircraft for an extended and perhaps finite transition. Furthermore, market forces served by the proposed architecture incentivizes legacy users be fully IAMS-compliant. Such an integrated approach provides for continuous movement toward the end state of full compliance with IAMS objectives, and avoids the inherent risks of a “step” change in system usage that a “flip-the-switch” approach incurs when a new system is developed to its ultimate end state in parallel with an existing system. Wholesale transition to new equipment is costly and likely to be resisted, thereby significantly delaying the formulation of an integrated system for efficient flow of vehicles. The “flip-the-switch” approach also encourages a federated system consisting of several segmented domains with diverse architectures, thus denying benefits to most users and delaying economic growth for the Nation.

An argument might be made that there should be several systems that serve the needs of different users, and interface between different systems could be achieved through “hand-off” protocols. Rather than the management for vehicle distribution and flow being integrated, affected domains would be elements within a federation of systems. Time and energy spent on “hand-off” protocols, however, detracts from the overall benefits of developing an integrated system that encompasses all users, including legacy vehicles. A unified system avoids the real risk of creating “silos” of interest and provides management efficiencies by integrating the needs of all users within an overarching architecture.

While the authors of this study believe an integrated system, such as proposed, offers the most efficient and productive way forward to serve the needs of UAS, ODM and legacy vehicles now and in the foreseeable future, we welcome vetting of the IAMS architecture against contrarian positions.

**Summary**

Public demand for Unmanned Aerial Systems has led to approximately 1 million additions to the Federal Aviation Administration’s aircraft registry during the last 18 months. While most of those vehicles were purchased by hobbyists, approximately 100,000 were for commercial purposes. The FAA forecasts that the commercial UAS fleet will approach 500,000 units by 2021. As the number of traditional aircraft remains relatively stable at about 210,000 vehicles, the UAS fleet is growing dramatically.
In January of this year, the Aeronautics Research Mission Directorate received a report entitled *NASA Strategic Framework for On-Demand Mobility*, which presented the case for technologies enabling anyone to fly anywhere, anytime for productivity or pleasure. The report asserts that enabling greater mobility, particularly in areas not served by schedule airlines and unlikely to be served by them, would bring significant economic and quality-of-life benefits to U.S citizens.

Demand for new efficiency in distribution and transportation is growing, and with that demand comes a need for an architecture that accommodates large numbers of new vehicles, including those operating autonomously and possessing the potential to create and serve On-Demand Mobility. Such demand also offers the opportunity to develop a vehicle-centric system that employs satellites for precision positioning, high-speed processing, networked data communications technology and autonomous-vehicle design to create an efficient and dynamic distribution system expanding services all across America.

IAMS is a concept that addresses the management and distribution of UAS, ODM vehicles and legacy aircraft in a highly effective architecture for all forms of distribution, independent of vehicle design or transportation mode.

This chapter presents architecture for management and control, which it identifies as the Integrated Advanced Mobility System (IAMS).

The IAMS vision serves to guide NASA research that will achieve a future environment for the movement of vehicles through any domain that satisfies IAMS requirements. Pursuit of the IAMS vision will refine and shape NASA’s activities in the area of On-Demand Mobility and map the route to full definition and feasibility. A set of meaningful measures of success will be established and, as alternatives for the vision are examined, the measures of success will be used to select the most promising. Policy alternatives need to be explored as part of the IAMS research since policies will have a significant impact on the architecture.

ODM stakeholders will have to support and be partners in the development of and transition to the vision. Before starting IAMS research, the vision and measures of success should be vetted and modified to ensure specific interest and needs are met.

Pursuit of the IAMS vision will refine and shape NASA’s activities in the area of On-Demand Mobility and map the route to safe and efficient distribution of people and packages for high definition ODM. Meaningful detours to the path that achieves a functional and efficient system of On-Demand Mobility will be explored, and appropriate metrics will be established. With research and development focused on the IAMS vision, NASA will respond to market forces and public expectation, thereby facilitating economic development and improved quality of life.

**Findings and Recommendations**

*Finding 2.1—The number of Unmanned Aerial Systems added to the inventory of U.S registered aircraft approached one million units in the last 18 months, mostly but not exclusively for recreational purposes, and is expected to grow dramatically in the near future.*

*Finding 2.2—By 2021, the FAA forecasts that the commercial UAS fleet will grow to 500,000.*
Finding 2.3—Researchers following the growth of UAS characterize the innovations associated with UAV/UAS vehicles as a disruptive technology, and the harbinger of a new Global distribution system.

Recommendation 2.1—Management and control of all vehicles within the National Air Space (NAS) should be unified and vehicle centric.

Recommendation 2.2—Today’s human controller-centric system of air traffic management and control should be transitioned to an integrated and vehicle centric system that enables the movement of all aerial vehicles including UAS, ODM and conventional aircraft.

Recommendation 2.3—Research and development of the proposed Integrated Advanced Mobility System (IAMS) should be pursued by NASA.

Recommendation 2.4 - NASA should vet the Study Team vision and measures of success with all stakeholders including the consumers and beneficiaries of ODM.

Recommendation 2.5 – NASA should design and implement a demonstration program best described as an X-NAS (Experimental National Airspace System) that employs experimental vehicles capable of ODM performance operating within an IAMS environment. Such an effort will require a dedicated test area, eventually expanding to examine real-world scenarios.
CHAPTER 3 – ODM CONCEPT, DEMAND AND AIRSPACE LOADING CONSIDERATIONS

Introduction

NASA’s request for an assessment of demand and airspace loading considerations derived from the ODM requirements immediately generates what Harvard Business School Professor Clayton Christensen defined as “The Innovator’s Dilemma”. Before a capability is available, there is an absence of data with which to estimate demand.

Clearly, legacy and traditional demand forecasting depends on historical data, and legacy data cannot accurately reflect demand for services not yet possible. Nor are data available that fully envision all potential users and beneficiaries of services not yet operational. Just as demand for cell phones would not have been accurately mapped before the devices and service became ubiquitous, it would be cavalier to suggest empirical demand for a fully deployed ODM architecture.

Further complicating the estimate, the descriptive language of today’s transportation and distribution systems is bounded by current technology and regulatory “realities” that, when applied to ODM, unnecessarily constrain the potential innovation and realization of a vision the authors articulate in Chapter 2. ODM is more than the description of a “vehicle”. ODM is, in fact, an architecture in which legacy, UAV/UAS and vehicles with ODM performance characteristics can be accommodated.

ODM is a distribution environment for people and packages optimized for purpose of movement, exploiting appropriate technologies, operational capabilities and other variables to assure safe and efficient transit on and above the surface for the movement of people and packages. For vehicles that can meet designated “measures of success” of the ODM architecture, full system benefits can be achieved. Other participating and nonparticipating vehicles may be accommodated, though constrained by having to meet residual legacy or sub-optimal operational requirements.

Just as the inevitable success of the Internet or cell phones could not be adequately forecast, neither can the latent demand for ODM capabilities. This architecture is explained in Chapter 2. Its favorable consideration should not be damped by the legacy demand and airspace loading discussion which follows. Due to the realities in forecasting introduced above, the use of the term ODM in this analysis is somewhat limited and is not fully consistent with the term’s use in Chapter 2, which imagines near ubiquitous application of an ODM architecture.

The following analysis is a relatively narrow, high level assessment of airspace loading, for illustrative purposes. It does not define the real breadth of ODM vehicle and operational concepts, which span the gamut of sizes, speeds, ranges, payloads and business models. Nor does the analysis directly address the important ODM Concept of “modeless” connectivity.

Despite these caveats and the aforementioned limits on availability of data directly applicable to the envisioned future, this analysis provides a compelling argument for aggressive pursuit of research and investment in ODM, as it is described in Chapter 2.
Current Demand Estimates

The estimated demand for ODM and UAS vehicles for the entire globe, the United States, and India were prepared and presented as part of the initial report from this project. Table 3.1 below summarizes these results, while Table 3.2 contains relevant operational assumptions about the aircraft used supporting the demand estimates. But it is important to note that the configuration of travel options on which these demand results are based assume only air vehicles.

<table>
<thead>
<tr>
<th>Table 3.1 – US Annual Expected ODM Demand (1,000’s)</th>
<th>2015</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Markets</td>
<td>239</td>
<td>480</td>
</tr>
<tr>
<td>Total Trips</td>
<td>3,570</td>
<td>29,008</td>
</tr>
<tr>
<td>Total Pax</td>
<td>5,452</td>
<td>46,292</td>
</tr>
<tr>
<td>Total Revenue</td>
<td>$902,536</td>
<td>$5,198,547</td>
</tr>
<tr>
<td>Total Markets W/o Nonstop Service</td>
<td>178</td>
<td>403</td>
</tr>
<tr>
<td>ODM Only Markets</td>
<td>136</td>
<td>367</td>
</tr>
<tr>
<td>ODM Only Trips</td>
<td>218</td>
<td>1,737</td>
</tr>
<tr>
<td>ODM Only Pax</td>
<td>334</td>
<td>2,797</td>
</tr>
<tr>
<td>ODM Only Revenue</td>
<td>$56,731</td>
<td>$324,193</td>
</tr>
</tbody>
</table>

Intraurban markets not included
Table 3.2 – ODM Aircraft Attributes, Passenger Characteristics, and Fare

<table>
<thead>
<tr>
<th>Aircraft Attributes</th>
<th>2015</th>
<th>2035</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Passengers</td>
<td>3</td>
<td>4</td>
</tr>
<tr>
<td>Maximum Range</td>
<td>600 nm</td>
<td>600 nm</td>
</tr>
<tr>
<td>Range Reduction per Passenger</td>
<td>45 nm</td>
<td>45 nm</td>
</tr>
<tr>
<td>Cabin Comfort Level</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Cruising Speed</td>
<td>3.0 nm/min</td>
<td>3.0 nm/min</td>
</tr>
<tr>
<td>Time to Cruising Altitude</td>
<td>6 min</td>
<td>6 min</td>
</tr>
<tr>
<td>Time from Cruising Altitude</td>
<td>6 min</td>
<td>6 min</td>
</tr>
<tr>
<td>Passenger Characteristics</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aircraft Acceptance</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>ODM Availability Awareness</td>
<td>0.1</td>
<td>0.7</td>
</tr>
<tr>
<td>Mean Commercial Air Access Time</td>
<td>240 min</td>
<td>240 min</td>
</tr>
<tr>
<td>Mean ODM Airport Access Time</td>
<td>70 min</td>
<td>70 min</td>
</tr>
<tr>
<td>Fare Structure</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ODM Base Fare</td>
<td>$25.00/trip</td>
<td>$25.00/trip</td>
</tr>
<tr>
<td>ODM Fare/nm travel distance</td>
<td>$0.91/nm</td>
<td>$0.62/nm</td>
</tr>
</tbody>
</table>

A search of the literature found only a few references that discussed the share of travel modality attributable to automobiles versus aircraft in markets served by air travel, scheduled or otherwise.

One study offers the graph shown in Figure 3.1, but notice that the distance between the origin and the destination varies from 100 to over 1000 miles, far beyond the distances considered in intra-city travel. Note that the mode split between automobiles and air is roughly linear except for the lower and upper tail. (It should be noted that this study was exploring the impact of the 9/11 attack on air travel, which explains the distance range being considered.)

The data in Figure 3.1 does give us at least a general idea of the mode split between automobiles and aircraft. Note in the graph on the left that below 300 miles, about 10% of the trips would be made by air (if such were available). The right-side graph reflects the effects (presumably) of the 9/11 attack, which have now most likely dissipated, except for the delays associated with security screening. If that 10% has maintained, then, given the results from the original NIA study, we could assert that the mode split between automobiles and air vehicles for trips of about 300 miles would be about 10%. This implies, for example, that the largest air market in the world, between San Francisco and Los Angeles, represents about 15% of all travel between these two metropolitan areas. In the AirMarkets demand model,
during the standard week\footnote{The “standard week” is the second week in August, which has nominal travel for summer activities but is least likely to contain a special occasion (e. g. holiday) that would distort the travel estimates. The standard week also contains, historically, 1/31 of the travel in a city pair observed per year.} this market produces 138,000 air trips between this city pair, and thus there about 920,000 total trips by auto in a standard week, or some 28 million per year.

Prior proprietary research was performed into the number of individual travel parties that would be likely to travel by air if it were available, based on the distributions found for travel group size, income, and the relationship between the importance of time and money. At this early stage, it was found that about 15\% of all travelers would opt for ODM air if they were aware of it and it was available. That means that, of the roughly 20,000 people who travel each day by air between San Francisco and Los Angeles, 2950 of them would opt for ODM service, yielding 1745 estimated trips per day (at the mean of 1.69 persons per trip). This gives at least a first-cut approximation of the demand for ODM service in that market. But it is only a first cut. Much more research is needed. And, of course, at issue is the air traffic control for such a travel pattern.

The distribution of the demand for air travel as a function of air trip length in the United States is illustrated in greater detail in Figure 3.2. Notice that only a tiny fraction of the travel, less than one-tenth of one percent, would be made by ODM if the trip length is less than 75 miles. In other words, intra-urban air travel is virtually unknown for short journeys.

\begin{center}
\includegraphics[width=\textwidth]{figure3.1}
\end{center}

\textbf{Figure 3.1 – Estimated Mode Split between Air and Automobile Travel}
Due to the limitation in available data for calibration of demand modeling methods in this report, the emphasis is not on intra-urban electric ODM and UAS vehicles. The issue of the distribution of the proportion of travel between modes of travel – air vehicles, personal automobiles, taxi services, mass-transit bus service, and high-speed rail service – is the vital component of any demand analysis. It has also been the subject of urban transportation analysis for the at least the last seven decades.

The Virginia Tech University Air Transportation Systems Laboratory produces estimates of intra-urban air travel based on commuter traffic. Their recent report estimates ODM demand based on the traffic demand estimates done by local agencies. In particular, they are based on mode splits between car and transit, but ODM air will offer a travel experience that is qualitatively different from either of these modes, in terms of comfort, safety, noise, privacy, etc. In a mode-choice model it is often the case that a term of reference, the alternative-specific constant (ASC) captures contributions to utility that are specific to the given mode under consideration. These are often significant, as they represent many of the aforementioned factors like comfort and safety. It is not reasonable to assume a value for an ASC without data, and assigning the ASC for ODM air to be equal to that of car travel or transit travel will lead to erroneous predictions. Given the present state of demand technology, there is no available alternative to this method, and it turns out that intra-urban air demand far exceeds any estimates of availability for the foreseeable future. Estimates by AirMarkets using its agent-based model for on the intra-urban landscape suggests about 15% of all travel could be of interest to intra-city travelers. In a city of one million population, that amounts to roughly 300,000 trips per day. Yet there is no attempt by local agencies to institute intra-urban air service. Suffice it to say that methods and tools used to estimate ODM demand are at best feeble.

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Appendix B to this report discusses the problem of modeling mode split for auto vs. air travel in the context of intra-city travel in substantial detail. An acceptable model does not now exist, because up to now there has been no opportunity to offer such options to intra-city travelers. An effective solution will require substantial effort in data collection and analysis using a stated preference survey approach coupled with an advanced travel behavior logit-based agent simulation. This is one of the most important conclusions of this chapter of this report.

**Current Airspace Loading Estimates**

The volume of potential intra-city ODM flights predicted by nascent demand studies strongly suggests that new airspace procedures, structures and technologies will be needed. To illustrate the magnitude of the challenge, consider the example of San Francisco, California. A recent study by Virginia Tech that examined the demand for intra-city ODM in a 17-county region of Northern California including the San Francisco Bay Area shows that ODM has the potential to achieve a 0.5%-4% market share of all commuter trips if aircraft per-mile operating costs can be kept between $1.00 and $1.25. This conclusion was based in part on considering households with family incomes greater than $100,000 as the candidate market for ODM. In San Francisco County itself, the number of households with incomes over $100,000 is approximately 170,000. Presuming a single commuter per household, we could expect 340,000 trips per day (to and from work) for these households, neglecting individuals working from home, and recognizing that many of these trips would remain within San Francisco County. Presuming 4% market share results in 13,600 trips. With Virginia Tech’s presumed load factor of 2.4 passengers per flight, we could therefore expect greater than 5,600 flights/day via ODM aircraft. Presuming an evenly distributed 12-hour daily operational timeframe (which admittedly smears the peak demand of rush hours), this demand results in an average of approximately 470 flights per hour or nearly 8 flights/min either to, from, or within San Francisco County. In a rush hour peak, it would not be unreasonable to expect more than double this flight frequency.

To consider the implications of this flight frequency on airspace loading, we must first examine the current ideas being suggested for how intra-city ODM aircraft will operate with the airspace. An excellent recent paper by Mueller, Kopardekar, and Goodrich, "Enabling Airspace Integration for High-Density On-Demand Mobility Operations," AIAA-2017-3086, outlines four possibilities for ODM integration into the airspace: (1) Increasingly automated IFR operations, (2) Increasingly automated VFR operations, (3) expanded UTM-like services, and (4) a hybrid strategy that leverages aspects of strategies (1) – (3) as appropriate and advantageous. In the discussion below, we focus primarily on strategies (1) and (2) because they have the greatest connection to current airspace constructs.

Considering an approach leveraging IFR operations, Mueller *et al.* indicate the challenge in Figure 3.3 shown below for the example of San Francisco. Current IFR procedures include a 3-nm terminal area separation requirement per 1,000 ft. altitude layer. As shown in Figure 3.3, imposing this separation requirement for a takeoff and landing area near the geographic center of San Francisco effectively excludes aircraft from operating anywhere else in the city in the same altitude band at the same time. Our demand estimate of 8 flights/min derived above lacks adequate resolution to ascribe the number of flights entirely contained within San Francisco vs. arriving or departing at any one time; however, it is nonetheless apparent from the magnitude of this number that tens of flights may need to be airborne above the city.
simultaneously. This consideration implies that the practicality of ODM airspace management based strictly on current IFR procedures is infeasible, necessitating new ODM-specific features, such as those discussed by Mueller.

Additionally, from an airspace loading standpoint, an IFR-based integration strategy would strain existing airspace management resources; Mueller et al. state that the entirety of the low-altitude sectors 40 and 41 within Oakland Center (illustrated on the right in Figure 3.3) have a maximum capacity of 15-25 aircraft. With our conclusion that San Francisco itself could have tens of simultaneous ODM flights in the airspace, we might reasonably anticipate that the entire bay area could have hundreds or even thousands of simultaneous flights. Indeed, Virginia Tech estimates that at 4% market share, their 17-county (primarily Bay Area) study region would demand 133,000 flights per day (~11,000 flights per hour or ~180 flights per minute if averaged over a 12-hour operational period). Mueller et al. presume a “high-density” ODM scenario of 1200 aircraft operating simultaneously in major metropolitan areas such as the San Francisco Bay area—about one aircraft per square nautical mile in contrast to the typical enroute center average of one aircraft per 250-500 nmi². The magnitude of these flight counts dwarf current operational expectations. Comparing to the 15-25 aircraft capacity of sectors 40 and 41 in Oakland Center, it is clear that current levels or even reasonable increases in human resources (flight controllers) critical to airspace services would be vastly inadequate for at-scale ODM operations. Automation of IFR airspace services would certainly be necessary, even if terminal and enroute separation requirements could be relaxed to the needed levels.

We now consider the airspace loading aspects of ODM integration through increasingly automated VFR operations (Mueller et al.’s second strategy), again based on the example of the San Francisco area. VFR flights must remain outside of controlled airspace unless specifically granted permission to enter. The implications of this requirement for ODM operations in the San Francisco area are stark. Figure 3.4 shows the Bay Area airspace. It is dominated by the large Class B surrounding SFO, with the Oakland and San Jose Class C’s also occupy large areas. Several Class D airspaces at San Carlos, Palo Alto, Moffett, Livermore, and Reid-Hillview are also present. The result is that very little low-altitude Class
G airspace would be available for VFR-based ODM flight. The available VFR airspace is largely restricted to the narrow paths shown as blue arrows in Figure 3.4. A VFR-based ODM integration paradigm would likely dramatically increase the number of flights through these corridors, which would require substantively reduced aircraft separation compared to typical VFR operations. As discussed by Mueller, separation in VFR is the responsibility of the pilot, with the guideline of remaining “well clear” of other traffic as a subjective judgment. The magnitude of potential ODM traffic that could need to transit the narrow VFR airways in the San Francisco area is a clear indication of the pressing need for accurate in-aircraft sense-and-avoid sensors and associated autonomy, as discussed by Mueller.

An additional disadvantage of restricting ODM flights to narrow VFR corridors is that the route detour penalty compared to great circle distance can be significant; for example, as shown in Figure 3.4, a flight from east of Oakland constrained to these corridors would need to detour considerably northbound to avoid the OAK Class C and the SFO Class B, resulting in a range penalty as high as 100%. Considering that most envisioned intra-city ODM vehicles are battery electric VTOL aircraft with limited range capability, this restriction may significantly impact ODM market feasibility in the near term. One possible solution to the challenges noted above would be to open limited corridors through the Class B and Class C airspaces for VFR-based ODM traffic; however, this strategy would require considerable study of specific needs for ODM routes coupled with careful consideration of traffic within the controlled airspaces, including approach paths.
We now turn our attention from intra-city ODM to inter-city ODM, via the example of flights between San Francisco and Los Angeles. As noted in Section 3.2, we have estimated a demand for 1745 daily inter-city ODM flights between LA and San Francisco, a distance of 350-400 miles depending on the particular origin and destination airports. Typical current commuter flights between these regions operate at block speeds near 300 mph, resulting in flight times of approximately 1.2 hours. These commuter flights follow IFR flight plans and cruise at a typical altitude of 25,000 ft. in Class A airspace controlled by Oakland Center and Los Angeles Center. With consideration of current levels of controller workload and staffing, a typically sized enroute sector has a capacity of 10 to 20 aircraft, with larger sectors (in terms of volume) having generally greater capacity. Presuming that the 1745 flights per day occur over a 12-hour operational window, the hourly flight rate is 145 flights per hour. Considering a flight time of ~ 1 hour, it is therefore reasonable to presume ~150 inter-city ODM flight could be expected to be simultaneously airborne in the route between LA and the Bay Area. Typical flight routes span 2-3 sectors; presuming that inter-city ODM aircraft have performance similar to current turboprop commuter aircraft (and that they therefore operate in Class A airspace), we could therefore expect that inter-city ODM aircraft at this estimated level of demand would load current high-altitude enroute sectors by an additional 50-75 aircraft. This flight count surpasses current ARTCC sector capacity levels by as much as 2.5x to 7.5x.

Now turning to approach and departure control, we consider as a baseline that the Southern California TRACON supports 2.2 million flights per year, or approximately 250 flights per hour.\textsuperscript{10} From the considerations above, inter-city ODM operations might be expected to result in an additional 150 flights per hour to this demand. These rudimentary analyses make it clear that new airspace management procedures, technologies, equipment, and/or staffing levels are required to support the additional demand for air traffic services associated with high levels of ODM operations.

**Findings and Recommendations**

The following conclusions, then, result from the above analysis.

*Finding 3.1 - The demand for intra-urban air travel is difficult to predict without detailed studies of consumer demand in each market. It appears that there could be demand for 5,600 ODM flights in San Francisco County alone using one recent methodology funded by NASA.*

*Finding 3.2 - The demand for inter-urban ODM travel is also difficult to estimate at this time, but under reasonable assumptions concerning automobile and aircraft usage, as many as 1,700 ODM trips per day could occur between Los Angeles and San Francisco markets.*

*Finding 3.3 - Despite these caveats and the aforementioned limits on availability of data directly applicable to the envisioned future, the analyses of this chapter provide a compelling argument for aggressive pursuit of research and investment in ODM*

*Recommendation 3.1 - Given the state of urban travel demand methodology, an advanced intra-urban travel model is recommended. Currently, a Structural Equation Model (SEM)*

\textsuperscript{10} FAA Aviation Data and Statistics at FAA.gov
based behavioral logit model is considered state of the art. That approach should be evaluated and a process for its development recommended.

Recommendation 3.2 - The model must be built using data generated by a properly designed and executed stated preference survey of sufficient sample size.

Recommendation 3.3 - The design of the state preference survey should be undertaken as the next step in intra-urban ODM demand analysis.
CHAPTER 4 – NASA UAS PROJECTS AND OUTCOME ALIGNMENTS WITH ODM NEEDS

Introduction

NASA has been working with Unmanned Aerial Vehicles (UAV) and Unmanned Aerial Systems (UAS) for decades. With the advent of the FAA’s roadmap to UAS Integration in 2013 and with the FAA Reauthorization Act of 2014, the stage was set to truly integrate commercial UAS activities within US airspace on a large scale. This entirely new industry is largely driven by the prospect of potentially large revenues. Multiple financial ratings agencies and institutions have concurred that the UAS industry will reach over $100B in annual sales by 2026 (based on 10-year projections from 2016) and aircraft unit sales will also exceed 1 Million annually as well. In fact, recent FAA estimates have stated that there are currently approximately 750,000 small UAS (under 55lbs/25kg) already registered in this sector, with 100,000 of those being used in commercial operations. By contrast, there are approximately 210,000 manned aircraft registered in the US system, with little to no chance of the same exponential growth paths as projected by UAS.

Figure 4.1 – UAS Industrial Revenue Forecast

Current NASA UAS Activities

NASA is involved in the newest aviation sector – UAS - and is somewhat engaged in research on ODM (not defined as suggested by this report) piloted and unpiloted operations. Those current areas include Sense and Avoid Systems, Human Systems Integration, C2 Command and Control Platforms, sUAS Technologies, and advancements in Miniaturization, Certification and Unmanned Traffic Management Operations.

The reader should note that the term “On Demand Mobility” (ODM) is used in this Chapter in a nearer term context than the term is used elsewhere in this report (e.g., in Chapter 2). Specifically, in this Chapter ODM applies more to the “vehicle” component, particularly to UAV/UAS vehicles in an ODM application, rather than as a future ODM environment or architecture.

See and Avoid

“See and Avoid” has been the basis of separations used since the dawn of powered flight. In basic terms, “See and Avoid” requires a pilot to see reference points, surface, obstacles and other air traffic (which presumes that adequate visibility is available for the task). While considered adequate for VFR traffic, and as the backup even for instrumented flight, the pilot’s awareness of other traffic and obstacles is diminished with workloads, environmental/weather restrictions to visibility, by cockpit and aircraft structural designs, or in the case of UAV/UAS, when viewing the situation from a remote or telepresence vantage point.

Procedural Separation

Before, and in the early days of radar air traffic control, “procedural separation” (separation by assignment of times over known points and assigned altitudes) was the means of separating aircraft enroute, supported by voice communications, and backed up, of course by “See and Avoid.” Air traffic were issued clearances that specified positions at NavAids or intersections of airways, and pilots conformed to assigned times at clearance limits, or “held” enroute to achieve separation. Today, procedural separation can still be applied in some airspace or in lost communications situations. Procedural separation depends on accurate navigation and confidence in pilot proficiency, with communications providing air traffic control its awareness of aircraft locations. To that extent, and even though FAR 107 currently only allows for direct line of sight operations, many sUAS systems incorporate sophisticated visual and ultrasonic proximity sensors to help avoid objects. It is still incumbent upon the pilot of the sUAS to visually avoid other aircraft.

Radar Separation

After development of radar in WWII, air traffic control applied radar technology to scan airspace and detect aircraft, using “skin paint” or “primary” radar, the radar reflection of aircraft as a mechanism for location and separation. Procedural separation and “see and avoid” still played important roles in assuring aircraft separation. Primary radar targets provided a relatively gross location requiring greater separation standards than were possible with the advent of transponders and “secondary” radar with discrete “coded “squawks,” which increased displayed positional accuracy and aircraft data, including identification, altitude and speed. Radar separation still requires voice communications capability and constant radio contact with ATC.

Sense and Avoid
Another level of air traffic separation (defined as a distance or time between vehicles that eliminates the risk of collision) and opportunity for terrain or object avoidance can be derived from application of several systems including Advanced Collision Avoidance Systems (ACAS), Enhanced Ground Proximity Warning Systems (EGPWS) and ADS-B.

ACAS communicates with other nearby aircraft targets and works out an avoidance flight path with any potential conflicting aircraft automatically. This type of technology has very real potential applications for UAS and ODM environments as it can be initiated without a human in the loop; and advanced processors could enable Machine-to-Machine (M2M) interactions.

Enhanced Ground Proximity Warning System (EGPWS) is another standalone, independent system that uses a worldwide terrain and obstacle database. It is based on aircraft relative position and provides a pilot with “escape” maneuvers. This system can also play a safety role on UAS and ODM aircraft and to some degree is already implemented in higher end UAS aircraft. Instead of warning the pilot of impending collision risk, it directs the UAS to simply stop or avoid an area by turning away. Thus, this technique has significant potential safety implications for future ODM operations.

Automatic Dependent Surveillance—Broadcast (ADS-B) is a current Radar replacement technology for aircraft surveillance. In base form, ADS-B takes aircraft position (GPS) and intent data and autonomously transmits these data via an enhanced transponder on 978 MHz (UAT) or 1090 MHz (ATC standard response frequency), depending on the class of aircraft. This system can provide a very accurate view of aircraft without a Primary or Secondary Surveillance Radar requirement. The UAT version of ADS-B is considered a likely candidate for UAS and ODM traffic as it is primarily focused on lower altitude GA traffic today. Very small (down to 20 grams) UAT transmitters (ADS-B –out) are currently available to sUAS operators.
ADS-B Air Operations with UAT and 1090ES

The potential shortfall of ADS-B lies in density of traffic, which could lead to saturation of the ADS-B network. While 794 Ground ADS-B controllers (GBTs) are currently deployed, they can only handle about 3000 users each and are limited to line-of-site – potentially a problem for low altitude operations. A modified version of ADS-B software might be used to track these low altitude and high density aircraft utilizing GPS position reporting already fed into the cellular data network that could be used as the transport mechanism. At the present time, ADS-B data are easily (and real-time) viewable via an inexpensive receiver. It is conceivable that for sUAS traffic, to minimize power requirements, the aircraft could house the ADS-B out transmitter, and the pilot ground control system (GCS) could house the ADS-B in receiver to interpolate and make traffic avoidance decisions. These potential flight path changes would then be sent to the sUAS via the command and control (C2) link. There are also current programs to receive the traffic information on the sUAS itself, allowing for localized avoidance decisions given the proper software and computing capability.

The ODM imagined by this paper, predicated on self-negotiated separation, however, would likely require greater accuracy than these systems currently provide.

Another option for aircraft tracking might be to use a commercial service such as FlightAware that reads and sorts current traffic, although with potential delays, and transmits the information to the UAS pilot/operator. A hybrid option for the near future would be to utilize the cellular based tracking mechanism on lower risk traffic such as sUAS, and use certified ADS-B on other pilotless ODM vehicles – as currently exists on other manned aircraft.

In all cases, surveillance data could be processed on UAS and ODM vehicles to reduce link latency and potential loss of signal issues. These data would then continuously feed the unit’s flight controllers (i.e., flight management systems) directly with potential escape and avoidance maneuvering trajectories. Industry groups such as RTCA SC-228 are actively working many of these issues.

Sense and Avoid for UAS and ODM vehicles should contain several layers of protection. NASA activities in this area are summarized in Appendix A.

Human Systems Integration

Human Systems Integration or Human Factors play an extremely important role in today’s very complex aircraft and sophisticated worldwide ATC communications system. The nature of human systems integration will change significantly with ODM and will represent new research challenges. Since the mid 80’s, multi-crew operations (such as FAR 121 or FAR 91 Business Jet Operations) have depended on a Captain managing the flight and utilizing the input of ATC, flight officers, dispatchers, meteorologists, maintenance centers, etc. This Triad of operations, including the aircraft, Operations Control Centers and the Air Traffic provider, supported by the management principals of Crew Resource Management (CRM), have led to a safer and more reliable air transportation system. The principal of CRM could be applicable to UAS and ODM operations. In addition to Multicrew CRM, it is suggested that ODM and UAS operators consider using Single Pilot Resource Management. Single-pilot resource management (SRM) is an adaptation of crew resource management (CRM) training to single-pilot operations. The purpose of SRM is to reduce the number of aviation accidents caused by
human error by teaching pilots about their own human limitations and how to maximize their performance. The initiative for this training began in 2005 when the NBAA published training guidelines for single-pilot operations of very light jets (VLJs).\(^{12}\)

Without precluding future developments, it is noted that the operations triad of aircraft, Ops Center and Air Traffic Management can still exist and would function even more effectively using digital telephony and Internet Protocol as the communications layer. The pilot role could still exist, but instead of relying on other crew members and cabin staff, a ground-based pilot might control multiple flights and rely extensively on the aircraft sensors as the information source. NASA currently has many Human Systems/Factors projects underway; this report will focus on those specifically involving Unmanned UAS or Pilotless ODM like projects.

NASA currently has activities in this area summarized in Appendix A.

**C2 Command and Control Platforms**

Command and Control (C2) is the essence of today’s remote pilot operations. For the pilot to be removed from the aircraft, it is important that this C2 link support a minimally capable “telepresence” to the vehicle. While most UAS and ODM aircraft will fly completely via auto-flight, the Ground Control System (GCS) should initially be able to take guidance suggestions from a pilot and be able to utilize the telemetry link to provide a virtual cockpit display to the ground-based operator. This C2 link must be robust, have range beyond the max

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distance between the operator and aircraft, and be immune to reflectivity and multipath-loss issues. It is also imperative that the C2 link live in the aviation-protected spectrum and have enough bandwidth to support basic controls to and telemetry back from the aircraft. Of note, there are currently several proposals and operation using non-protected public use spectrum such as 916Mhz, 2.4Ghz, and 5Ghz, as well as cellular 4G and LTE C2 links.

Communications between a drone operator and vehicle is analogous to VHF pilot-ATC communication. It is also important that alternatives in the event of link loss be employed. A common response to C2 loss is that the UAS will return to its takeoff point and land after a 10 second interruption in the C2 signal. There are several workgroups working the C2 issue, most importantly RTCA SC-228, Work Package-2. Additionally, this group has published a whitepaper on using the link on aviation protected spectrum such as VHF and 5Ghz (C-Band).

NASA currently has many activities in this area summarized in Appendix A.

Small UAS Technologies and Advancements

Small Unmanned Aircraft (sUAS) are by FAA definition an unmanned aircraft weighing less than 55 pounds on takeoff, including everything that is on board or otherwise attached to the aircraft. small Unmanned Aircraft System (small UAS) are small unmanned aircraft and its associated elements (including communication links and the components that control the small unmanned aircraft) that are required for the safe and efficient operation of the vehicle in the national airspace system.

The ability to autonomously fly a sUAS has existed for years, but miniaturization and advancements in smartphone technology has accelerated drone revolution. Examples of the tech component miniaturization are found in small, very powerful microprocessors, Microelectromechanical Systems (MEMS), GPS, cameras, Wi-Fi and the 4G/LTE links. NASA can play a key role in this technology and is actively involved in areas of interest including small scale aerodynamics, flight controls, autonomous operations, optimal angle of attack flight, VTOL, failure modes, etc.

NASA currently has activities in this area summarized in Appendix A.
Unmanned Traffic Management

Many companies, some well-established and experienced in the arena of Air Traffic Management and Control as well as others with significant resources but less participation in ATM/ATC, are exploring how they might participate in the integration of UAS and traditional aircraft. See Figure below:

It is critical that some “unified” architecture for the Nation’s (perhaps the global) distribution system be articulated and evolved. Equally important is the requirement that the emerging architecture for all vehicles operating in the airspace not necessarily be constrained as an evolution of the current NAS or even NextGen. Rather, the future “unified” construct should
serve the needs of all vehicles within its domain and exploit innovation in communications, information, computer and aerospace technology (perhaps from UAV/UAS investments) to achieve On-Demand Mobility and safety objectives.

Today’s architects, users and managers of the U.S. National Airspace System must address how current and legacy vehicles can be safely and productively incorporated into a future U.S. National Distribution System (e.g., system of ATM/ATC), exploiting the full benefits of ODM for safety, security, economy, environment, American leadership and mobility. The conceptual Air Traffic Control architecture future of UAS/ODM aircraft can be found in Chapter 2 Integrated Advanced Mobility System (IAMS).

**NASA UTM/UAS Projects and Outcome Alignments with ODM Needs**

For purposes of this paper, the authors carefully considered NASA ARMD strategies for integrating UAV/UAS into the NAS, other planning and briefing materials, including Strategic Thrust 1: Safe, Efficient Growth in Global Operations, Strategic Thrust 6: Assured Autonomy for Aviation transformation, as well as ARMD FY 2018 Program and Resource Guidance:

1. As with other documents and background reviewed by the team, very tight focus on “integration” of UAV/UAS into the NAS tends to constrain the range of proposed research investments in a manner supportive but not specifically emphasizing the need for longer term architecture development and research investments specifically in ODM.
2. Currently available technologies, such as sense and avoid, detect and avoid, ADS-B, etc. present possible solutions for UAV/UAS separation or collision avoidance in the NAS but likely will not be adequate to satisfy the Measure of Success in this paper’s projected ODM environment.
3. Much of the research suggested in the references above is based or dependent on current procedure, airspace design and regulatory structures, and human centric operations and control, which the authors of this paper think will require significant evolution to enable their proposed ODM environment, particularly since a mature ODM deployment would essentially be an autonomous system*. Research to satisfy current and legacy system constraints is not likely to be sufficiently forward compatible to support ODM system opportunities and /or requirements.
4. The references also place significant emphasis on airspace stratification (altitude separation) whereas mature ODM implementation will require freeing participating vehicles from assigned trajectories, altitudes, speed controls or routes. Virtually none of the research for vehicles or airspace management currently included in the references targets technologies or procedures to achieve this critical ODM component.
5. Despite having the limitations described above, the authors found considerable agreement with elements of vision contained in the ARMD Cohesive Full UAS Integrated Strategy.
6. The authors also agree that efforts to demonstrate public benefit, and to achieve public acceptance and confidence, expressed in the references, are essential contributors to introduction of UAS/UAV and ODM.
7. The authors support NASA research to support higher TRL level vehicle technologies and efforts to support demonstrations and operationalization. However, NASA
investments should focus on vehicle research that achieves longer term ODM capabilities and performance.

8. Investments suggested by the references in X-System development and demonstrations, research in autonomy, and in Capstone like, mission oriented, predefined, efforts could contribute significantly to introduction of ODM. The following graphic from the ARMD Integration Strategy is as appropriate for ODM as it is for UAS.

*The need to minimize human intervention in ODM is critical. As recently as 30 August, Chris Hart, former Chairman of the NTSB, is quoted to have said “the fact is that automation is generally able to operate best in a completely automated environment, with little or no human involvement, such as with an airport people mover. Aviation experience has

13 ARMD Presentation “Cohesive ARMD Full UAS Integration Strategy”
demonstrated that the challenges are much more daunting when automation is operating in an environment that also has extensive human involvement”.\footnote{http://www.thedrive.com/tech/13903/what-can-self-driving-cars-learn-from-aviation, August 30, 2017}

**Relevant Research:** In October 2016 researchers associated with NASA’s Ames Research Center, Moffett Field, CA conducted a series of flight tests with multiple unmanned aircraft systems (UAS) at the Reno Stead Airport UAS Test Range in Reno, Nevada. Flight tests, which were conducted over a period of five days, examined the feasibility of operating multiple UAS beyond visual line of sight (BVLOS) of their respective operators. Data collected were part of NASA’s ongoing efforts to evaluate air traffic management concepts designed to enable UAS operations with the National Airspace System (NAS). The effort was sponsored by the United States National Aeronautics and Space Administration Unmanned Aircraft Systems Traffic Management (UTM) Project.

The explosive growth of UAS necessitates focused attention, such as the Reno Flight Tests, on how such vehicles will be operated in the National Airspace System. Concepts of UAS Traffic Management (UTM) will pace the extent to which UAS will facilitate our nation’s economy and quality of life as elements within an advanced distribution and delivery system for materials (such as packages and agricultural aids) as well as for surveillance and routine inspections. Furthermore, concepts of UTM will shape how larger autonomous vehicles envisioned to serve On-Demand Mobility will be operated with in the NAS.

Findings and recommendations from the Reno study, as summarized below, are relevant to the formulation of future research and policy considerations.

- Some level of information sharing between operators was needed to ensure that operational behavior of nearby UAS was known and predictable. Since the Reno test vehicles were under the control of ground-based operators, flight crews communicated with other operators to share intent data as well as to confirm a vehicle’s altitude and to review contingency management procedures.
- Researchers determined a need to display airspace position and flight information among the Reno operators. The study identified the benefit of communications among operators during off-nominal conditions, thereby greatly improving their ability to react to hazardous conditions caused by other users of the airspace.
- Inconsistencies in measuring and reporting vehicle altitude presented a problem. A suitable UTM must provide a means whereby all vehicles are either using the same references for elevation determination, not only for vehicle separation but also for terrain clearance, or are negotiating separation based on common position data in all dimensions. Where altitude stratification is required there must be accurate and timely information sharing between UAS and other vehicles.
- UAS are exposed to localized weather conditions that often (if not always) differ from weather observed or forecast from a central location. Researchers noted that operators can measure atmospheric conditions on the ground and look at local weather reports from distant sensors, but the UAS will be operating in its own localized (i.e., micro) weather environment. A UAS needs to be able to sense and adjust to its unique situation. In other
words, UAS need situational sensing capabilities. Such situational data should be shared with other users of the airspace.

- Research results from the Reno flight tests also demonstrated that operational plans were not always consistent between UTM System, Ground Control Stations and UAS. Thus, a need existed to de-conflict operations by expanding the regions around the flight geography of vehicles operating with a sector. Flight test revealed that only 54 percent of vehicles remained within the desired flight geography. During the remaining 46 percent of flights, the UAS left its flight geography at least once during the mission. Expanding “Conformance Geography” and “Protected Geography” associated with human involvement with UTM produces inefficiencies.

**Observations Regarding Reno Tests:** The Reno Flight Test generated results that, in the opinion of the Study Team, are truly meaningful in shaping the course of future research regarding UAS and eventually ODM within the NAS.

First, UAS must communicate with each other and with other relevant vehicles in order to operate safely and efficiently. To ensure accuracy, consistency and processing speed, such communications should be done without human intervention.

Second, further research along the line of the Reno tests, as well as studies yet to be defined should be accomplished using simulation, thereby generating considerably more data at less cost per data-point than actual flight tests.

The Reno UAS study is reflective of NASA research regarding UTM, illustrating why future analysis should focus on a unified system encompassing all vehicles operating within the NAS.

**Other NASA Efforts:** The Study Team also examined the finding the UAS Team of Community Experts against the airspace, air vehicle, policy and regulatory need of On-Demand Mobility: Study Team observations are presented below:

1. The Community of Experts, by nature of their composition and population of stakeholders interviewed had a limited objective, which was to advocate for “integration of UAV/UAS into the NAS”.
2. The paper focuses on “community” (UAV/UAS) needs, not broad public benefit, and does not aggressively project a vision of future mobility needs.
3. The paper does not adequately question whether the current NAS, or even NextGen, is capable of accomplishing “integration of UAV/UAS” minus operational and regulatory penalties that delay or deny potential benefits or economies specifically enabled by UAV innovation.
4. The paper, by fully endorsing FAA’s mantra of “integration into NAS” unwittingly perpetuates the NAS/NextGen rather than making the bold call for a new, unified, mode-agnostic architecture in which participating vehicles negotiate separation and true free flight is possible, and where legacy vehicles are accommodated (until attracted by benefit to meet participation requirements).
5. The paper describes “integration” in terms that imply retention or minor modifications of today’s’ airspace, regulatory, and infrastructure definitions and constraints. This inherently delays discovery by research and innovation of benefits for which technologies exist or are emerging today, but which are not deployable in the current NAS or NextGen
6. While the Experts seek autonomous operations, it is in the context of UAV/UAS and in less than an aggressive way. Nor does the paper enthusiastically define autonomous operations, or a time line for introduction or deployment.

7. The paper emphasizes the need for pilot and controller training, again in a UAV/UAS context. This satisfies the “integration” agenda, for the near term but tends to suggest long delays in the advent of autonomous operations, which our effort suggests is a nearer term ODM requirement.

8. The paper unfortunately urges NASA to conduct “highest priority research required to support UAV/UAS integration into the NAS.” This will deplete resources necessary and important to the longer-term investments essential to ODM.

This approach prevented the Experts from fully projecting UAV/UAS innovation and discovery into a future architecture not constrained by legacy NAS or NextGen, nor unconstrained by current regulatory or procedural strictures. Their enthusiasm for championing UAV/UAS opportunity, and encouraging research and actions to counter FAA reluctance and public perceptions of UAS/UAV seems to have discouraged latent energy to seek the more ambitious future our team imagines and describes.

The Team of Experts’ hint at longer range objectives were obscured by their energy to assure FAA acceptance of UAV/UAS “integration”, but their suggestions are still useful springboards for the proposition we have put forth in this chapter below. Some of the most interesting “hints” may even be statements that support an aggressive ODM investment proposition. They include:

1. The Experts stipulate that there is a lack of “common framework” for integration of UAV/UAS into the NAS. We have written of that gap as lack of “a target architecture.”

2. The Experts state clearly that “FAA legacy systems will need to be updated”, and we have indicated that legacy systems are not adequate to meet the pace of industry technology advance, nor ODM requirements.

3. The Expert’s paper “begs” for an ambitious National target architecture, by suggesting autonomy, new connectivity, and bandwidth needs and application of new technologies to legacy challenges in the NAS.

4. The Team of Experts warns NASA to “avoid the constraints of only researching solutions for the near term”, but to “…look beyond to a world where all aircraft are not piloted but are flown by on-board automation”.

5. The paper hints at longer range objectives, research and actions that are not unique to UAV/UAS but may be critical to ODM as well.

6. The paper introduces Policy, Planning and Regulatory considerations, many of which are also applicable to ODM, but which are presented in the context only of UAV/UAS.

7. The Team of Experts were less than consistent in their discussions of application of “sense and avoid” and “detect and avoid”, but their interest in those technology/procedural mechanisms for separation lean in favor of our “negotiated separation” ODM scheme, and suggest they would likely support investment and adoption for UAV/UAS.
8. The Team of Experts agreed, as we do, that government (NASA/FAA) are not moving at the pace of industry innovation.

**Summary Regarding Team of Experts Report:** The objective of the report was so narrowly focused on “integration of UAV/UAS into the NAS” that opportunity for longer term thinking was severely constrained. Still the Experts tangentially provided strong support for many of the points raised, discussed and captured in our instant report. Clearly UAV/UAS are an important step toward the ODM architecture we postulate, and innovation provoked in the deployment and safe/efficient operation of all classes of UAV/UAS, whether piloted, or autonomous, will answer many important research questions for ODM. That said, the Experts warning to NASA should not go unheeded…. sacrificing future benefits by over spending on near term solutions would be unfortunate. NASA is best when it stretches imagination and reaches for the greatest challenge. Our paper, in particular Chapter 2, presents ODM and a systems architecture we call IAMS as that challenge.

**Identifying Current Needs and the ODM – UAS Technology Gaps**

NASA should pursue research and development of an advanced architecture that supports safe integration of UAS and proposed ODM vehicles into a “unified” environment while accommodating legacy vehicles until such time that benefits of the advanced architecture attract necessary performance and equipage for full compliance by all participants. There are three phases – INITIAL, NEAR, and LONG TERM.

The INITIAL Phase is based on blending UAS operations into the NAS where possible. The FAA has started this process through the section 333 waiver process and has created FAR 107 for the governance of basic commercial UAS operations for sUAS – aircraft weighing less than 55 lbs. (25 Kg). The rules for these operations are simple; –

- Must not fly over populated areas
- Must remain within 400’ of the surface and 400’ of an object or building
- Must be observed by sUAS operator
- Must operate during daytime with visibility of at least 3 miles
- Must be able to maintain unaided visual sighting between operator and aircraft at all times
- The sUAS may not operate within 5 miles of an airport

The NEAR-TERM Phase as proposed here will expand on the FAR 107 rule set and consider additional operational elements including beyond visual line of sight (BVLOS), night operations, flights over populated areas, flights in controlled airspace and flights into reduced visibility (similar to IFR operations). This operational expansion starts to increase the practicality of UAS operations and allows for a framework for unmanned aircraft that more closely resembles todays manned aircraft rules for transport of people.

NASA UTM Projects in the near term are working in the following areas:

1. **SYSTEM CERTIFICATION** – This area of focus is the overall certification for UAS operations. The framework must address how the public can be assured of safe and reliable operations while allowing for unique new sUAS, larger UAS, and ODM-capable vehicles. The overall system must achieve a safety and reliability factor at
least as good or better than today’s manned operations, and must accommodate legacy vehicles during the transition from existing ATM/ATC architecture to a future advanced architecture.

2. SYSTEM SAFETY MANAGEMENT (SMS) - SMS is the formal, top-down, organization-wide approach to managing safety risk and assuring the effectiveness of safety risk controls. It includes systematic procedures, practices and policies for the management of safety risk. Safety Management System (SMS) is a standard discipline throughout the aviation industry worldwide. It has been recognized by the Joint Planning and Development Office (JPDO), International Civil Aviation Organization (ICAO), and civil aviation authorities (CAA) and product/service providers as the next step in the evolution of safety in aviation. SMS is also a standard for the management of safety beyond aviation. Similar management systems are used in the management of critical areas such as quality, occupational safety and health, security, environment, etc. SMS should be a consideration of an advanced architecture for all vehicles operating in the NAS.

Safety Management Systems (SMS) for product/service providers (certificate holders) and regulators will integrate modern safety risk management and safety assurance concepts into repeatable, proactive systems. SMS emphasize safety management as a fundamental business process to be considered in the same manner as other aspects of business management.

By recognizing the role of process in accident prevention, SMS provides both certificate holders and FAA:

- A structured means of safety risk management decision making
- A means of demonstrating safety management capability before system failures occur
- Increased confidence in risk controls though structured safety assurance processes
- An effective interface for knowledge sharing between regulator and certificate holder
- A safety promotion framework to support a sound safety culture
3. SYSTEM SECURITY – It is imperative that the system for the operation of sUAS and ODM contain extensive elements of security to ensure the public in the vehicles and within the proximity of vehicles will be safe. Beyond physical security, which the Transportation Security Administration (TSA) is responsible for today, UAS and ODM operations must have robust data security. Understanding how data and hacker breaches could possibly impact UAS and ODM operations is key to ensuring the viability of such operations in the future.

4. AIRSPACE MANAGEMENT PROCEDURES – Airspace Management is the true integration of these new aircraft types and vehicle modes into our current airspace system. Chapter 2 of this report deals extensively with this subject. Basically, the system needs to look to the future of these vehicles to determine how they will safely and procedurally interact with legacy vehicles. While many options need to be carefully considered, the most desired outcome will be a unified system where legacy operations will be accommodated in a new UAS and ODM architecture.

5. IMPLEMENT AIRSPACE CHANGES – The implementation of UAS and ODM into the existing NAS will require significant changes to procedures, except when operations are segregated, mechanisms for which do not adequately exist today. Such changes need be the topic of additional research. Consideration must be given to allowing ODM and UAS distribution of passengers and packages into current airports, as well as to and from a myriad of new departure and arrival points in a networked system. Today, there are several key UAS flight trials of concepts such as Beyond Visual Line of Sight (BVLOS) and automated NOTAM filing systems to allow for UAS flight within 5NM of airports vs. a blanket prohibition, but because these are narrowly focused on current UAV/UAS vehicles and operational capabilities, these fall short of ODM system needs.

6. OPERATIONAL AND AIRSPACE MANAGER TRAINING PROGRAMS AND IMPLEMENTATION – the current FAA ATO has an extensive set of training and currency requirements for all the people involved in operations and maintenance of the ATC System. These requirements range from routine currency events and checks to...
special training for integration of new procedures. Special consideration must be given to the sheer magnitude of training that will be required for these personnel to understand how transition and new rules need to be implemented, all while maintaining current operations. Design of an advanced architecture will need to consider the design, cost and efficiency of Operational and Airspace Manager training, with attention to the transition to and eventual eliminating such human involvement in an autonomous system.

7. FAA ‘OVER THE FENCE’ IMPLEMENTATION RULES – These new rule sets might allow some blending of traditional manned aircraft operations with UAS and ODM vehicles, but it is unlikely that they will permit the sort of imagined new vehicles and autonomy suggested in Chapter 2.

8. ESTABLISH OPERATOR REQUIREMENTS – Current rules do not adequately outline the operational requirements of operators in the way the FAA parts 61, 91, 121,135, 141, and 142 do. The operational requirements and some semblance to the experiences of traditional aviation must be considered for the operators of UAS and ODM vehicles during transition to an advanced architecture that can facilitate autonomous movement of all vehicles, particularly where these vehicles will carry people and interact with traditional manned aircraft. The establishment of these requirements and procedures will then require the training and currency of the operators. Development of an integrated system that enable advanced mobility should not be constrained, however, by legacy thinking.

The LONG-TERM PHASE proposed here involves an advanced architecture that accommodates UAS and ODM vehicles and ODM mission concepts. A future can be imagined where traditional pilot and air traffic controller roles are addressed through automation, and human involvement is focused on mission definition. This future state will require extensive development in automation and communications, navigation and surveillance systems.

NASA must embrace and research a strategy to support this future, while working extensively to blend this new technology into the continually evolving current operations. In its role, NASA will need to work with the FAA to update FARS/ACS/ORDERS in FAR 107 for UAS, FARs 23, 61, 91, 135 for ODM, and potentially even FAR 121 for pilotless large transport aircraft. Such work will require extensive enablement of technical standards for UAS and ODM aircraft to meet or exceed today’s current manned capabilities, agreement with curriculums for all of the programs, pilot and medical requirements for all remote operations, eventual complete integration into airspace, and even worldwide harmonization through standards bodies such as ICAO.

The outcomes of NASA UAS ODM programs have far reaching implications. The following questions deserve consideration:

i. SYSTEM CERTIFICATION – How do we build a certification process similar to manned aviation, yet progressive enough to incorporate new technologies, and autonomous and remote operations?

ii. SAFETY – What are the overall acceptable safety metrics (Are those suggested in Chapter 2 adequate?) How is the public (flying and on the ground) to be assured that these new systems can meet or exceed current manned aircraft standards?

iii. SECURITY – Is the system “hack-proof”? Can these systems be utilized for nefarious reasons? Are there fail safes to stop bad operations?
iv. PILOT AND/OR OPERATOR QUALS – Current manned pilot training is complex and well established. Is it, and will it continue to be adequate in the future to simply issue a certificate based on a knowledge test? Will that suffice for BVLOS (IFR) type of operations where the aircraft will likely interact with others? What will be the certification process and level for ODM autonomous passenger or distribution operations?

v. AIRSPACE MANAGEMENT – Will airspace definition and management look at all like it does today? How will management or control be invoked by controllers, or will it all be automated, monitored by humans?

vi. OPERATIONAL CRITERIA – What are the rule sets? Fail safes? Failure modes?

vii. ENABLING ACTIVITIES – What technologies and procedures are in place today that can assist in establishing the architecture of tomorrow? What projects can NASA be involved in to encourage and accelerate adoption of new aircraft, technologies and capitalize on today’s UAV/UAS innovation?

viii. FUTURE ACTIVITIES – NASA should look 10, 20, 50 years to the future, contribute to an enthusiastic effort to define a target architecture for 25 and 50 years and contribute to articulation of a viable pathway for deployment of millions of these aircraft. What are the plans for that future? What if, the majority of aviation vehicles are Unmanned and Unpiloted in 25 years?

Summary

Current demand for Unmanned Aerial Systems and the expected demand for On Demand Mobility will lead to significant changes in traditional aviation. It is estimated that over 100,000 UAS vehicles are currently in commercial operation, and that number is expected to grow exponentially over the next years. Such activity will require extensive changes to the guidance and rule sets to achieve a safe and seamless integration into the US airspace. Many factors will need to be considered including the role of the pilot, avionics systems, standards, all-weather operations, training, system safety, and required performance levels of pilotless manned and unmanned systems.

Furthermore, research to address the growth of UAS must not inhibit thinking directed at development of a fully integrated system capable of accommodating all vehicles.

The demand for efficient distribution and new forms of transportation is growing, and remote pilot operations will be an early part of that demand as well as a step toward more autonomous operations. Advances in miniaturization of avionics and processors, largely in part due to advancements in components for smart phones, as well as rapid advancements in propulsion and airframe materials are provoking for significant adaptation and deviation from traditional manned aircraft. These new technologies will offer significant public benefit, and they may be valuable in perpetuating utility and operational use of legacy forms of manned aviation.

Safety systems and levels also must be considered a high priority. Reliance on SMS programs to assign a risk level is required. Small UAS vehicles can accept a certain tolerance to failure, while larger vehicles with human occupants will need to have a much higher level of safety. NASA and other research investments are needed to assure new aircraft systems impose no new or higher risk when operating in legacy airspace. Accommodation of large numbers of
autonomous vehicles, both unmanned and manned, with varied different operating characteristics and technologies will provoke opportunities for a variety of new research activity.

Findings and Recommendations

Finding 4.1 – NASA performs considerable UAS research but it is not adequate to address the needs of ODM.

Finding 4.2 ODM concepts require certain autonomy and automation capabilities not envisioned in current NASA and FAA technology planning.

Finding 4.3 – NASA’s UAS technology research is focused on the relatively near term. Technology research that does not take advantage of the rapid evolution of communication, networking and cockpit automation is not adequate to address the needs of ODM.

Finding 4.4 - UAS have surpassed the number of manned systems and are expected to grow exponentially. These aircraft will be integrated into current airspace and likely will be given consideration for access to underutilized or otherwise unused airspace (specifically low altitude) where they can operate autonomously and be managed on an exception basis. These operations offer opportunity for research and demonstration that could inform ODM vehicle, procedure and research investment.

Finding 4.5—Current Operational and training standards (for which there is a significant amount of work already done) should be the basis for future aircraft operations. This body of work and platform should inform any new requirements imposed by new aircraft and technologies such as UAS and ODM

Finding 4.6—UAS aircraft can accept a higher risk tolerance than vehicles carrying humans, yet they are still restrained by not compromising the safety of manned aircraft. The technology applicable to UAS is leading to the development of manned ODM aircraft with much of the same vehicle characteristics as drones. It is imperative that this new technology and integration into existing systems must meet or exceed current safety standards for manned aviation to protect humans in the vehicle and in proximity to these operations. Simply put, the technology must be able to meet or exceed current safety levels without a human pilot presence to take over in the event of a systems failure.

Finding 4.7 – The cycle pace at which a NASA research program can proceed must be increased to stay in touch with the rapid advancements in UAS and ODM technologies by industry. Traditional multi-year programs may not be adequate to keep pace with the commercial sector.

Recommendation 4.1—Establish a new set of standards working groups for ODM vehicles. These groups must look innovatively at highest level operations, training and safety standards.

Recommendation 4.2—Allow for integrated operations in traditional airspace, while considering only near term exclusionary airspace for UAS and ODM vehicles to encourage introduction of advantage of new technologies and automation systems.
Recommendation 4.3 – Establish system Required Performance Levels for this new breed of UAS and ODM similar to the Required Communications, Navigation and Surveillance levels that are established for today’s manned aircraft, but not constrained by today’s methods to achieve those levels of safety.

Recommendation 4.4 – NASA should initiate more projects with ODM architecture, technology and vehicle focus. Research focused on UAS provides a springboard for investments in ODM propulsion, communications and separation/avoidance technologies recognizing On-Demand Mobility, as a potential modeless distribution/movement concept as well as a vehicle design, and as the next logical step in the aeronautics growth path.
CHAPTER 5 - CONCLUSIONS, SUMMARY AND RECOMMENDATIONS

Introduction

This chapter draws conclusions from the findings and recommendations of Chapter 1 through 4, in the context of the purpose of the study, namely:

- Discuss how the high priority needs for UAS integration align with the needs for ODM.
- Review the UAS Independent Team of Community Experts report against the airspace, air vehicle, policy and regulation needs of ODM.
- Assess the alignments between the current and planned NASA UAS efforts and the needs in the ODM domain as well as describe other significant areas that should be addressed to achieve the goals of ODM.

Our conclusions are based on our review of existing NASA research activities related to UAS airspace operations and ODM-related vehicle concepts and their operational implications, as well as numerous other reports on current industrial advancements and thinking. We consider the emerging and converging technologies that will enable advancements in the safety and efficient operations of ODM vehicle concepts, including but not limited to autonomy and automation, connected aircraft (“Internet of Airborne Things”), and related regulatory, policy, and infrastructure considerations. Finally, we consider the significant societal needs for bold and new thinking affecting mobility in our future.

Conclusions

We conclude that the current activities in development of UAS airspace operating capabilities will contribute to, but not adequately provide for the needs of the emerging ODM concepts. These ODM concepts include the urban VTOL and inter-urban VTOL and CTOL vehicles and operations being developed by industry today, as well as those envisioned by private and public-sector leaders for the future. We understand that the challenges of changing the NAS to both accommodate and stimulate market opportunities in the ODM and UAS domains are daunting from organizational, policy, regulatory and financial perspectives. However, we also see the current strategic context that frames the need and opportunity for ODM and UAS capabilities have reached a crescendo of sorts, making now a time for some of the boldest action by the aeronautics community in many decades. That strategic context includes the need for mobility innovations that can drive our economy to new levels of productivity and growth, the need for solutions to the effects of transportation on the environment, and the need for a unified system of vehicle-centric Air Traffic Management and Control.

The market pull for ODM and UAS innovations is driven in large part by providing mobility options that have never been available for the public before, and that would solve many social and environmental challenges facing our legacy transportation systems. These challenges include costs in time, energy, productivity, carbon and related impacts on quality of life.

The technological push for ODM and UAS innovations span the full spectrum of vehicle, infrastructure, manufacturing, operations, and related safety and efficiency impacts. The reason we can now imagine these options is due in the main to emerging and converging
technologies that enable the needed changes being developed outside of traditional aeronautics enterprise sources, bringing with them economies of scale otherwise difficult to achieve in aviation domains.

**Recommendations**

What can NASA do to accelerate the progress toward the solutions space for the public needs in aeronautics-enabled advancements? We suggest three areas of opportunity for NASA’s investments to make a difference in the safety, reliability, performance, efficiency, and public acceptance of the emerging ODM and UAS capabilities. These areas include opportunities to lead, collaborate, as well as to follow in supportive ways.

**Lead:**

Transition from today’s human operator and controller-centric system of air traffic management and control to an integrated, vehicle-centric system that enables the movement of vehicles including UAS, ODM and conventional aircraft.

- Build on the current UTM and full integration of UAS in the NAS activities to create an experimental National Airspace System test bed (e.g., an “X-NAS”) in which multiple X-Plane / ODM vehicle and ATM concepts and related safety management systems can be evaluated for the spectrum of vehicles and operations being envisioned today.

**Collaborate:**

NASA can promote and organize requirements for investments in public transportation data, in advancing modal demand forecasting science and technology, and in understanding of the effects of the emerging technology-driven innovations on consumer acceptance.

**Follow:**

NASA can support their own and their public and private sector partner organizations’ agility for keeping pace during this epoch’s accelerating pace of change, through organizational experiments in how to partner and collaborate, in the interest of accelerated innovation processes. In the past NASA public-private collaborations, several closely related projects, programs, and funding sources were informally aligned to create a “constellation” of engagement approaches to progress. The AGATE, GAP, SATS, ERAST, SBIR/STTR, and similar projects in NASA’s past may provide some historical context for such thinking.

Below are the Findings and Recommendations, reproduced here by chapter, in one place.

**Chapter 1 – Introduction and Strategic Context**

*Finding 1.1 – The emergence within the recent few years of the industrial initiatives in ODM vehicle developments have not been matched by FAA and NASA initiatives that would support the airspace management system advancements required to support operations of large numbers of these aircraft in commercial or private service.*

*Finding 1.2 – The emergence of the UAS (or drone) industrial initiatives for vehicle concepts, mission concepts, as well as airspace management concepts provides a source of technology advancements in propulsion, control, manufacturing, communication, navigation, surveillance, and related airspace management systems concepts of relevance to the ODM visions and concepts.*
Finding 1.3 – The airspace management concepts being evaluated for UAS operations in the two NASA projects do not provide comprehensive satisfaction of the needs for ODM operations in both the urban and Inter-urban vehicle and mission concepts.

Chapter 2 – ODM Airspace Management Concept Description

Finding 2.1—The number of Unmanned Aerial Systems added to the inventory of U.S registered aircraft approached one million units in the last 18 months, mostly but not exclusively for recreational purposes, and is expected to grow dramatically in the near future. Finding 2.2—By 2021, the FAA forecasts that the commercial UAS fleet will grow to 500,000. Finding 2.3—Researchers following the growth of UAS characterize the innovations associated with UAV/UAS vehicles as a disruptive technology, and the harbinger of a new Global distribution system.

Recommendation 2.1—Management and control of all vehicles within the National Air Space (NAS) should be unified and vehicle centric.

Recommendation 2.2—Today’s human controller-centric system of air traffic management and control should be transitioned to an integrated and vehicle-centric system that enables the movement of all aerial vehicles including UAS, ODM and conventional aircraft.

Recommendation 2.3—Research and development of the proposed Integrated Advanced Mobility System (IAMS) should be pursued by NASA.

Recommendation 2.4 - NASA should vet the Study Team vision and measures of success with all stakeholders including the consumers and beneficiaries of ODM.

Recommendation 2.5 – NASA should design and implement a demonstration program best described as an X-NAS (Experimental National Airspace System) that employs experimental vehicles capable of ODM performance operating within an IAMS environment. Such an effort should have a dedicated test area, eventually expanding to examine real-world scenarios.

Chapter 3 – ODM Demand and Airspace Loading Assessment

Finding 3.1 - The demand for intra-urban air travel is difficult to predict without detailed studies of consumer demand in each market. It appears that there could be demand for 5,600 ODM flights in San Francisco County alone using one recent methodology funded by NASA.

Finding 3.2 - The demand for inter-urban ODM travel is also difficult to estimate at this time, but under reasonable assumptions concerning automobile and aircraft usage, as many as 1,700 ODM trips per day could occur between Los Angeles and San Francisco markets.

Finding 3.3 - Despite these caveats and the aforementioned limits on availability of data directly applicable to the envisioned future, the analyses of this chapter provide a compelling argument for aggressive pursuit of research and investment in ODM.
Recommendation 3.1 - Given the state of urban travel demand methodology, an advanced SEM-based behavioral urban travel model is recommended.

Recommendation 3.2 - The model must be built using data generated by a properly designed and executed stated preference survey of sufficient sample size.

Recommendation 3.3 - The design of the stated preference survey should be undertaken as the next step in intra-urban ODM demand analysis.

Chapter 4 - NASA UAS Projects and Outcomes Alignment with ODM Needs

Finding 4.1 – NASA performs considerable UAS research but it is not adequate to address the needs of ODM.

Finding 4.2 ODM concepts require certain autonomy and automation capabilities not envisioned in current NASA and FAA technology planning.

Finding 4.3 – NASA’s UAS technology research is focused on the relatively near term. Technology research that does not take advantage of the rapid evolution of communication, networking and cockpit automation is not adequate to address the needs of ODM.

Finding 4.4—Unmanned Aircraft Systems have surpassed the number of manned systems and are expected to grow exponentially. These aircraft must be integrated into current airspace and should be given some consideration for uninhibited access to underutilized or otherwise unused airspace (specifically low altitude) where they can operate autonomously and be managed on an exception basis.

Finding 4.5—Current Operational and training standards (for which there is a significant amount of work already done) should be the basis for future aircraft operations. This body of work and platform should inform any new requirements imposed by new aircraft and technologies such as UAS and ODM

Finding 4.6—UAS aircraft can accept a higher risk tolerance than vehicles carrying humans, yet they are still restrained by not compromising the safety of manned aircraft. The technology applicable to UAS is leading to the development of manned ODM aircraft with much of the same vehicle characteristics as drones. It is imperative that this new technology and integration into existing systems must meet or exceed current safety standards for manned aviation to protect humans in the vehicle and in proximity to these operations. Simply put, the technology must be able to meet or exceed current safety levels without a human pilot presence to take over in the event of a systems failure.

Finding 4.7 – The cycle pace at which a NASA research program can proceed must be increased to stay in touch with the rapid advancements in UAS and ODM technologies by industry. Traditional multi-year programs may not be adequate to keep pace with the commercial sector.
Recommendation 4.1—Establish a new set of standards working groups for ODM vehicles. These groups must look innovatively at highest level operations, training and safety standards.

Recommendation 4.2—Allow for integrated operations in traditional airspace, while considering only near term exclusionary airspace for UAS and ODM vehicles to encourage introduction of advantage of new technologies and automation systems.

Recommendation 4.3 – Establish system Required Performance Levels for this new breed of UAS and ODM similar to the Required Communications, Navigation and Surveillance levels that are established for today’s manned aircraft, but not constrained by today’s methods to achieve those levels of safety

Recommendation 4.4 – NASA should initiate more projects with ODM architecture, technology and vehicle focus. Research focused on UAS provides a springboard for investments in ODM propulsion, communications and separation/avoidance technologies recognizing On-Demand Mobility, as a potential modeless distribution/ movement concept as well as a vehicle design, and as the next logical step in the aeronautics growth path.
APPENDIX A – UAS LITERATURE SUMMARY

Introduction

This appendix summarizes the literature review on the technology domains in which the aeronautics research community has activities completed, underway or planned. These activities form part of the basis on which the findings and recommendations and conclusions are formed in this study.

Current NASA UAS Aircraft:

NASA has multiple UAS aircraft, from very small to large as testbed vehicle for UAS research. Below is a summary of some of the aircraft:

GLOBAL HAWK
NASA Strategic Framework for On-Demand Air Mobility

IKHANA/Predator B

Sense and Avoid Operations

_Daidalus Observations from Integration in the NAS Project Flight Test 4_: Michael Vincent, Dimitrios Tsakpinis; Published December 2016

Abstract: In order to validate the Unmanned Aerial System (UAS) Detect-and-Avoid (DAA) solution proposed by standards body RTCA Inc., the National Aeronautics and Space Administration (NASA) UAS Integration in the NAS project, alongside industry members General Atomics and Honeywell, conducted the fourth flight test in a series at Armstrong Flight Research Center in Edwards, California. Flight Test 4 (FT4) investigated problems of interoperability with the TCAS collision avoidance system with a DAA system as well as problems associated with sensor uncertainty. A series of scripted flight encounters between the NASA Ikhana UAS and various “intruder” aircraft were flown while alerting and guidance from the DAA algorithm were recorded to investigate the timeliness of the alerts and correctness of the guidance triggered by the DAA system. The results found that alerts were triggered in a timely manner in most instances. Cases where the alerting and guidance was incorrect were investigated further.

_Piloted Well Clear Performance Evaluation of Detect and Avoid Systems with Suggestive Guidance_: Eric Mueller, Confesor Santiago, Spencer Watza; Published October 2016

Abstract: This study evaluated the performance of four prototype unmanned aircraft detect-and-avoid (DAA) display configurations, each with different informational elements driven by alerting and guidance algorithms. Sixteen unmanned aircraft pilots flew each combination of the display configurations, with half being given zero DAA surveillance sensor uncertainty and the other half experiencing errors that were comparable, and in some cases slightly better than, errors that were measured in DAA system flight tests. The displays that showed intruder alert information in altitude and heading bands had significantly fewer losses of well clear compared with alternative displays that lacked that information. This difference was significant from a statistical and practical perspective: those losses that did occur lasted for shorter periods and did not penetrate as far into the geometric “separation cylinder” as those in
the non-banded displays. A modest level of DAA surveillance sensor uncertainty did not affect the proportion of losses of well clear or their severity. It is recommended that DAA traffic displays implement a band-type display in order to improve the safety of UAS operations in the National Airspace System. Finally, this report provides pilot response time distributions for responding to DAA alerts.

**SC-228 Defining the Collision Avoidance Region for Detect and Avoid Systems:** Davis Thipphavong, Andrew Cone, Chunki Park, Seung Man Lee, Confesor Santiago; Published August 2016

Abstract: Unmanned aircraft systems (UAS) will be required to equip with a detect-and-avoid (DAA) system in order to satisfy the federal aviation regulations to maintain well clear of other aircraft, some of which may be equipped with a Traffic Collision Avoidance System (TCAS) to mitigate the possibility of mid-air collisions. As such, the minimum operational performance standards (MOPS) for UAS DAA systems are being designed with TCAS interoperability in mind by a group of industry, government, and academic institutions named RTCA Special Committee-228 (SC-228). This document will discuss the development of the spatial-temporal volume known as the collision avoidance region in which the DAA system is not allowed to provide vertical guidance to maintain or regain DAA well clear that could conflict with resolution advisories (RAs) issued by the intruder aircraft’s TCAS system.

Three collision avoidance region definition candidates were developed based on the existing TCAS RA and DAA alerting definitions. They were evaluated against each other in terms of their interoperability with TCAS RAs and DAA alerts in an unmitigated factorial encounter analysis of 1.3 million simulated pairs. Based on the results of the analysis, the collision avoidance region definition for DAA systems below was recommended to and accepted by RTCA SC-228.

**UAS Human in the Loop Controller and Pilot Acceptability Study- Collision Avoidance, Self-Separation and Alerting Times:** James Comstock, Rania Ghatas, Michael Vincent, Maria Consiglio, Cesar Munoz, James Chamberlain, Paul Volk, Keith Arthur; Published April 2016

Abstract: The Federal Aviation Administration (FAA) has been mandated by the Congressional funding bill of 2012 to open the National Airspace System (NAS) to Unmanned Aircraft Systems (UAS). With the growing use of unmanned systems, NASA has established a multi-center "UAS Integration in the NAS" Project, in collaboration with the FAA and industry, and is guiding its research efforts to look at and examine crucial safety concerns regarding the integration of UAS into the NAS. Key research efforts are addressing requirements for detect-and-avoid (DAA), self-separation (SS), and collision avoidance (CA) technologies. In one of a series of human-in-the-loop experiments, NASA Langley Research Center set up a study known as Collision Avoidance, Self-Separation, and Alerting Times (CASSAT). The first phase assessed active air traffic controller interactions with DAA systems and the second phase examined reactions to the DAA system and displays by UAS Pilots at a simulated ground control station (GCS). Analyses of the test results from Phase I and Phase II are presented in this paper. Results from the CASSAT study and previous human-in-the-loop experiments will play a crucial role in the FAA's establishment of rules, regulations, and procedures to safely, efficiently, and effectively integrate UAS into the NAS.
Abstract: This study evaluated the effects of communications delays and winds on air traffic controller ratings of acceptability of horizontal miss distances (HMDs) for encounters between Unmanned Aircraft Systems (UAS) and manned aircraft in a simulation of the Dallas-Ft. Worth (DFW) airspace. Fourteen encounters per hour were staged in the presence of moderate background traffic. Seven recently retired controllers with experience at DFW served as subjects. Guidance provided to the UAS pilots for maintaining a given HMD was provided by information from Detect and Avoid (DAA) self-separation algorithms (Stratway+) displayed on the Multi-Aircraft Control System. This guidance consisted of amber “bands” on the heading scale of the UAS navigation display indicating headings that would result in a loss of well clear between the UAS and nearby traffic. Winds tested were successfully handled by the DAA algorithms and did not affect the controller acceptability ratings of the HMDs. Voice communications delays for the UAS were also tested and included one-way delay times of 0, 400, 1200, and 1800 msec. For longer communications delays, there were changes in strategy and communications flow that were observed and reported by the controllers. The aim of this work is to provide useful information for guiding future rules and regulations applicable to flying UAS in the NAS. Information from this study will also be of value to the Radio Technical Commission for Aeronautics (RTCA) Special Committee 228 – Minimum Performance Standards for UAS.
A Formally Verified Conflict Detection Algorithm for Polynomial Trajectories: Anthony Narkawicz, Cesar Muñoz; Published June 2015

Abstract: In air traffic management, conflict detection algorithms are used to determine whether or not aircraft are predicted to lose horizontal and vertical separation minima within a time interval assuming a trajectory model. In the case of linear trajectories, conflict detection algorithms have been proposed that are both complete, i.e., they detect all conflicts, and sound, i.e., they do not present false alarms. In general, for arbitrary nonlinear trajectory models, it is possible to define detection algorithms that are either sound or complete, but not both. This paper considers the case of nonlinear aircraft trajectory models based on polynomial functions. In particular, it proposes a conflict detection algorithm that precisely determines whether, given a look ahead time, two aircraft flying polynomial trajectories are in conflict. That is, it has been formally verified that, assuming that the aircraft trajectories are modeled as polynomial functions, the proposed algorithm is both sound and complete.

Characteristics of a Well Clear Definition and Alerting Criteria for Encounters between UAS and Manned Aircraft in Class E Airspace: Marcus Johnson, Eric Mueller, Confesor Santiago; Published June 2015

Abstract: Unmanned aircraft systems will be required to equip with a detect-and-avoid (DAA) system in order to satisfy the federal aviation regulations to remain well clear of other aircraft. For a DAA system to satisfy the requirement to stay well clear of other airborne traffic, a quantitative definition of well clear needs to be defined and evaluated. This study investigates the implications of UAS using proposed well clear definitions as a separation standard for conducting operations in the national airspace system. The first analysis considers three well clear definitions and presents the relative state conditions of intruder aircraft as they encroach upon the well clear boundary. The second analysis focuses on the definition of the alerting criteria needed to inform the UAS operator of a potential loss of well clear. All analyses are conducted in a NAS-wide fast-time simulation environment using UAS aircraft models, proposed UAS missions, and historical air defense radar data to populate the background traffic operating under visual flight rules. The results presented in this study inform the safety case, requirements development, and the operational environment for DAA minimum operational performance standards.

Characterizing the Effects of a Vertical Time Threshold for a Class of Well-Clear Definitions: Jason Upchurch, Cesar Munoz, Anthony Narkawicz, Maria Consiglio, James Chamberlain; Published June 2015

Abstract: A fundamental requirement for the integration of unmanned aircraft into civil airspace is the capability of aircraft to remain well clear of each other and avoid collisions. This requirement has led to a broad recognition of the need for an unambiguous, formal definition of well clear. It is further recognized that any such definition must be interoperable with existing airborne collision avoidance systems (ACAS). A particular class of well-clear definitions uses logic checks of independent distance thresholds as well as independent time thresholds in the vertical and horizontal dimensions to determine if a well-clear violation is predicted to occur within a given time interval. Existing ACAS systems also use independent distance thresholds; however, a common time threshold is used for the vertical and horizontal logic checks. The main contribution of this paper is the characterization of the
effects of the decoupled vertical time threshold on a well-clear definition in terms of (1) time to well-clear violation, and (2) interoperability with existing ACAS. The paper provides governing equations for both metrics and includes simulation results to illustrate the relationships. In this paper, interoperability implies that the time of well-clear violation is strictly less than the time a resolution advisory is issued by ACAS. The encounter geometries under consideration in this paper are initially well clear and consist of constant-velocity trajectories resulting in near-mid-air collisions.

Pilot Evaluation of a UAS Detect and Avoid Systems Effectiveness in Remaining Well Clear: Confesor Santiago, Eric Mueller; Published June 2015

Abstract: Unmanned aircraft will equip with a detect-and-avoid (DAA) system that enables them to comply with the requirement to "see and avoid" other aircraft, an important layer in the overall set of procedural, strategic and tactical separation methods designed to prevent mid-air collisions. Regulators will establish minimum operating standards for DAA effectiveness, but different combinations of algorithms, displays and procedures could be used to meet those standards. The research presented in this paper indicates the effectiveness of the combined pilot-DAA system as a function of the DAA design requirements and provides data that may be used to model the behavior of pilots when employing such systems. Two simulations involving 21 professional unmanned aircraft system (UAS) pilots evaluated eight different DAA system designs in order to assess their ability to maintain the "well clear" separation standard, i.e., the state of maintaining a safe distance from other aircraft that would not normally cause the initiation of a collision avoidance maneuver on either aircraft. When the traffic display was integrated with the primary mission map directly in front of the pilot, there were fewer losses of well clear. Greater warning time provided to the pilot was strongly correlated with success in remaining well clear. Pilots' ability to separate from aircraft with cooperative and non-cooperative surveillance systems was nearly the same after accounting for the amount of alert time provided in each encounter, although the limited surveillance volume for the non-cooperative aircraft meant alerts tended to occur later and therefore were more difficult to resolve.

A Family of Well-clear Boundary Models for the Integration of UAS in the NAS: Cesar A. Munoz, Anthony Narkawicz, James Chamberlain, Maria Consiglio; Published August 2014

Abstract: The FAA-sponsored Sense and Avoid Workshop for Unmanned Aircraft Systems (UAS) defines the concept of sense and avoid for remote pilots as "the capability of a UAS to remain well clear from and avoid collisions with other airborne traffic." Hence, a rigorous definition of well clear is fundamental to any separation assurance concept for the integration of UAS into civil airspace. This paper presents a family of well-clear boundary models based on the TCAS II Resolution Advisory logic. For these models, algorithms that predict well-clear violations along aircraft current trajectories are provided. These algorithms are analogous to conflict detection algorithms but instead of predicting loss of separation, they predict whether well-clear violations will occur during a given lookahead time interval. Analytical techniques are used to study the properties and relationships satisfied by the models.

Abstract: Most unmanned aircraft systems will be required to be equipped with a detect-and-avoid system that is capable of maintaining appropriate separation from other aircraft to operate in the National Airspace System. A surveillance system is one of the critical components of detect-and-avoid systems in order to predict potential conflicts with adequate lead time to remain “well clear” of other aircraft. The performance requirements of surveillance systems to detect and track intruder aircraft will depend on the encounter geometries that unmanned aircraft are expected to have with other aircraft in the airspace. In this study, a database of unmitigated encounters between unmanned aircraft and conventional manned aircraft operating under visual flight rules is created without maneuvering any aircraft to mitigate the risk of a separation violation. The encounter database is built through fast-time simulation of a large number of unmanned aircraft conducting various missions in the presence of historical visual flight rules traffic as recorded from live airspace operations. Analysis of the resulting encounter geometries suggests how the overall safety and performance of a surveillance system may relate to surveillance parameters such as surveillance range, horizontal and vertical fields of regard. This paper proposed and investigated potential safety and performance metrics for evaluating the performance of a surveillance system, such as the ratio of undetected and late-detected separation violations, and the time to violation at first detection for given sets of surveillance parameters. These example metrics demonstrate the utility of the database of encounters created in this work. It is expected that this database will be useful in the derivation of surveillance system requirements for detect-and-avoid systems.

Exploration of the Trade Space Between Unmanned Aircraft Systems Descent Maneuver Performance and Sense-and-Avoid System Performance Requirements: Devin P. Jack, Keith D. Hoffler, and Sally C. Johnson; Published May 2014

Abstract: A need exists to safely integrate Unmanned Aircraft Systems (UAS) into the United States' National Airspace System. Replacing manned aircraft's see-and-avoid capability in the absence of an onboard pilot is one of the key challenges associated with safe integration. Sense-and-avoid (SAA) systems will have to achieve yet-to-be-determined required separation distances for a wide range of encounters. They will also need to account for the maneuver performance of the UAS they are paired with. The work described in this paper is aimed at developing an understanding of the trade space between UAS maneuver performance and SAA system performance requirements, focusing on a descent avoidance maneuver. An assessment of current manned and unmanned aircraft performance was used to establish potential UAS performance test matrix bounds. Then, near-term UAS integration work was used to narrow down the scope. A simulator was developed with sufficient fidelity to assess SAA system performance requirements. The simulator generates closest-point-of-approach (CPA) data from the wide range of UAS performance models maneuvering against a single intruder with various encounter geometries. Initial attempts to model the results made it clear that developing maneuver performance groups is required. Discussion of the performance groups developed and how to know in which group an aircraft belongs for a given flight condition and encounter is included. The groups are airplane, flight condition, and encounter specific, rather than airplane-only specific. Results and methodology for developing UAS maneuver performance requirements are presented for a descent avoidance maneuver. Results for the descent maneuver indicate that a minimum specific excess power magnitude can assure a minimum CPA for a given time-to-go prediction. However, smaller amounts of specific excess power may achieve or exceed the same CPA if the UAS has sufficient speed to
trade for altitude. The results of this study will support UAS maneuver performance requirements development for integrating UAS in the NAS. The methods described are being used to help RTCA Special Committee 228 develop requirements.

**A Systems-Based Approach to Functional Decomposition and Allocation for Developing UAS Separation Assurance Concepts**: Seung Man Lee, Eric Mueller; Published August 2013

Abstract: In integrating Unmanned Aircraft Systems (UAS) into the National Airspace System, separation assurance is one of the important air traffic services for ensuring safe operations of air traffic. This paper describes an approach to develop a range of operational concepts by describing what functions and technologies are required to maintain safe separation of unmanned aircraft and how those functions are allocated and distributed across primary system elements, such as air traffic controllers, automation systems, aircraft onboard systems, and UAS ground control stations including UAS pilots. A framework proposed in this study identifies key functions and capabilities by decomposing high-level system goals into smaller functions to achieve them hierarchically and also identifies primary system elements to perform the identified functions by decomposing the whole system into smaller systems hierarchically. The framework represents hierarchical functional/physical structure and allocation of functions across system elements at different levels to generate a range of potential separation assurance concepts systematically. The detailed representation of functional decomposition and allocation enables an application of the framework for recommending levels of automation (LOA) developed based on human factors engineering principles. The detailed functional decomposition and allocation framework to develop a concept of operations provides additional analysis capabilities: stability, workflow, and task-load analysis to examine the completeness, correctness, and balance of functional decomposition and allocation schemes for concept development without requiring complex simulations. This paper demonstrates the framework through a case study of providing separation assurance functions for UAS operating in enroute and transition airspace in the Next Generation Air Transportation System (NextGen) timeframe.

**A TCAS-II Resolution Advisory Detection Algorithm**: Chamberlain, Cesar Muñoz, Anthony Narkawicz; Published August 2013

Abstract: The Traffic Alert and Collision Avoidance System (TCAS) is a family of airborne systems designed to reduce the risk of mid-air collisions between aircraft. TCAS–II, the current generation of TCAS devices, provides resolution advisories that direct pilots to maintain or increase vertical separation when aircraft distance and time parameters are beyond designed system thresholds. This paper presents a mathematical model of the TCAS–II Resolution Advisory (RA) logic that assumes accurate aircraft state information. Based on this model, an algorithm for RA detection is also presented. This algorithm is analogous to a conflict detection algorithm, but instead of predicting loss of separation, it predicts resolution advisories. It has been formally verified that for a kinematic model of aircraft trajectories, this algorithm completely and correctly characterizes all encounter geometries between two aircraft that lead to a resolution advisory within a given lookahead time interval. The RA detection algorithm proposed in this paper is a fundamental component of a NASA sense and avoid concept for the integration of Unmanned Aircraft Systems in civil airspace.
Investigating Effects of "Well Clear" Definitions on UAS Sense-And-Avoid Operations: Seung Man Lee, Chunki Park Marcus Johnson, Eric Mueller; Published August 2013

Abstract: Unmanned aircraft systems (UAS) will be required to equip with sense-and-avoid (SAA) systems in order to fulfill the regulatory requirement to remain “well clear” of other air traffic. This study investigates the effects that different well-clear metrics have on the rate of well-clear violations and evaluates the distribution of distances between aircraft at a well-clear violation in high-altitude enroute airspace. The first analysis determines the predicted rate at which violations of well clear would occur between UAS and manned aircraft operating under instrument flight rules, indicating the frequency with which a sense-and-avoid system would create a nuisance alert. This analysis is done both with and without an algorithmic model of air traffic control (ATC) separation provision services. The second analysis determines the relationship between time-based well-clear metrics and the range at which the violation would occur, a relationship that may inform the required SAA surveillance range and the frequency with which violations would occur despite ATC separation standards still being maintained. The analyses are carried out using a fast-time simulation capability of the entire US air traffic system over a single day, including 3000 UAS and more than 50,000 manned aircraft. Results indicate that, without any separation provision, a UAS would encounter a manned aircraft with a range $\tau$ (defined as the ratio of the relative range to range rate) of 60 seconds only every six hours. Approximately 75% of such encounters would occur outside the ATC separation standard of 5 nmi.

Concepts of Integration for UAS Operations in the NAS: Maria Consiglio, James Chamberlain, Cesar Muñoz, Keith Hoffler; Published September 2012

Abstract: One of the major challenges facing the integration of Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) is the lack of an onboard pilot that can comply with the legal requirement identified in the US Code of Federal Regulations (CFR) that pilots see and avoid other aircraft. UAS will be expected to demonstrate the means to perform the function of see and avoid while preserving the safety level of the airspace and the efficiency of the air traffic system. This paper introduces a Sense and Avoid (SAA) concept for integration of UAS into the NAS that is currently being developed by the National Aeronautics and Space Administration (NASA) and identifies areas that require additional experimental evaluation to further inform various elements of the concept. The concept design rests on interoperability principles that take into account both the Air Traffic Control (ATC) environment as well as existing systems such as the Traffic Alert and Collision Avoidance System (TCAS). Specifically, the concept addresses the determination of well clear values that are large enough to avoid issuance of TCAS corrective Resolution Advisories, undue concern by pilots of proximate aircraft and issuance of controller traffic alerts. The concept also addresses appropriate declaration times for projected losses of well clear conditions and maneuvers to regain well clear separation.

Human Systems Integration

UAS Pilot Evaluation of Suggestive Guidance on Detect and Avoid Displays: Kevin Monk, Zach Roberts; Published September 2016

Abstract: Minimum display requirements for Detect-and-Avoid (DAA) systems are being developed in order to support the expansion of Unmanned Aircraft Systems (UAS) into the
National Airspace System (NAS). The present study examines UAS pilots’ subjective assessments of four DAA display configurations with varying forms of maneuver guidance. For each configuration, pilots rated the intuitiveness of the display and how well it supported their ability to perform the DAA task. Responses revealed a clear preference for the DAA displays that presented suggestive maneuver guidance in the form of “banding” compared to an Information Only display, which lacked any maneuver guidance. Implications on DAA display requirements, as well as the relation between the subjective evaluations and the objective performance data from previous studies are discussed.

The Impact of Integrated Maneuver Guidance Information on UAS Pilots Performing the Detect and Avoid Task: Conrad Rorie, Lisa Fern; Published October 2015

Abstract: The integrated human-in-the-loop (iHITL) simulation examined the effect of four different Detect-and-Avoid (DAA) display concepts on unmanned aircraft system (UAS) pilots' ability to maintain safe separation. The displays varied in the type and amount of guidance they provided to pilots. The study's background and methodology are discussed, followed by the 'measured response' data (i.e., pilots' end-to-end response time in reacting to traffic alerts on their DAA display). Results indicate that display type had a significant impact on how long pilot's spent interacting with the interface (i.e., edit times).

An Evaluation of Detect and Avoid (DAA) Displays for Unmanned Aircraft Systems: The Effect of Information Level and Display Location on Pilot Performance: Lisa Fern, Conrad Rorie, Jessica Pack, Jay Shively, Mark Draper; Published June 2015

Abstract: A consortium of government, industry and academia is currently working to establish minimum operational performance standards for Detect and Avoid (DAA) and Control and Communications (C2) systems in order to enable broader integration of Unmanned Aircraft Systems (UAS) into the National Airspace System (NAS). One subset of these performance standards will need to address the DAA display requirements that support an acceptable level of pilot performance. From a pilot’s perspective, the DAA task is the maintenance of self-separation and collision avoidance from other aircraft, utilizing the available information and controls within the Ground Control Station (GCS), including the DAA display. The pilot-in-the-loop DAA task requires the pilot to carry out three major functions: 1) detect a potential threat, 2) determine an appropriate resolution maneuver, and 3) execute that resolution maneuver via the GCS control and navigation interface(s). The purpose of the present study was to examine two main questions with respect to DAA display considerations that could impact pilots’ ability to maintain well clear from other aircraft. First, what is the effect of a minimum (or basic) information display compared to an advanced information display on pilot performance? Second, what is the effect of display location on UAS pilot performance? Two levels of information level (basic, advanced) were compared across two levels of display location (standalone, integrated), for a total of four displays. The authors propose an eight-stage pilot-DAA interaction timeline from which several pilot response time metrics can be extracted. These metrics were compared across the four display conditions. The results indicate that the advanced displays had faster overall response times compared to the basic displays, however, there were no significant differences between the standalone and integrated displays. Implications of the findings on understanding pilot performance on the DAA task, the development of DAA display performance standards, as well as the need for future research are discussed.
In 2011 the National Aeronautics and Space Administration (NASA) began a five-year Project to address the technical barriers related to routine access of Unmanned Aerial Systems (UAS) in the National Airspace System (NAS). Planned in two phases, the goal of the first phase was to lay the foundations for the project by identifying those barriers and key issues to be addressed to achieve integration. Phase 1 activities were completed two years into the five-year project. The purpose of this paper is to review activities within the Human Systems Integration (HSI) subproject in Phase 1 toward its two objectives: 1) develop GCS guidelines for routine UAS access to the NAS, and 2) develop a prototype display suite within an existing Ground Control Station (GCS). The first objective directly addresses a critical barrier for UAS integration into the NAS - a lack of GCS design standards or requirements. First, the paper describes the initial development of a prototype GCS display suite and supporting simulation software capabilities. Then, three simulation experiments utilizing this simulation architecture are summarized. The first experiment sought to determine a base performance of UAS pilots operating in civil airspace under current instrument flight rules for manned aircraft. The second experiment examined the effect of currently employed UAS contingency procedures on Air Traffic Control (ATC) participants. The third experiment compared three GCS command and control interfaces on UAS pilot response times in compliance with ATC clearances. The authors discuss how the results of these and future simulation and flight-testing activities contribute to the development of GCS guidelines to support the safe integration of UAS into the NAS. Finally, the planned activities for Phase 2, including an integrated human-in-the-loop simulation and two flight tests are briefly described.

**UAS Measured Response: The Effect of GCS Control Mode Interfaces on Pilot Ability to Comply with ATC Clearances:** Lisa Fern, Conrad Rorie; Published October 2014

Abstract: The present study examined the effects of three different control mode interfaces on unmanned aerial system (UAS) pilots’ ability to comply with air traffic controller (ATC) traffic clearances. Pilots controlled a simulated UAS with a waypoint-only interface, an autopilot interface, and a manual, stick and throttle interface. Researchers recorded pilots’ ‘measured response’ at several stages of ATC-pilot interaction, which consisted of verbal response times, initial response times, initial edit times, total edit times, and overall compliance times. Results indicate that pilots are best able to comply with ATC clearances when provided with auto-pilot and manual control inputs. Limitations to the present study and future analyses are discussed.

**Air Traffic Controller Performance and Acceptability of Multiple UAS in a Simulated NAS Environment:** Vernol Battiste, Robert Jay Shively, Kim-Phuong L. Vu, Thomas Strybel, Dan Chiappe, Greg Morales; Published July 2014

Abstract: Previously, we showed that air traffic controllers (ATCos) rated UAS pilot verbal response latencies as acceptable when a 1.5-second delay was added to the UAS pilot responses, but a 5-second delay was rated as mostly unacceptable. In the present study, we determined whether a 1.5-second added delay in the UAS pilots' verbal communications would affect ATCos interactions with UAS and other conventional aircraft when the number
and speed of the UAS were manipulated. Eight radar-certified ATCos participated in this simulation. The ATCos managed a medium altitude sector containing arrival aircraft, enroute aircraft, and one to four UAS. The UAS were conducting a surveillance mission and flew at either a "slow" or "fast" speed. We measured both UAS and conventional pilots' verbal communication latencies, and obtained ATCos' acceptability ratings for these latencies. Although the UAS pilot response latencies were longer than those of conventional pilots, the ATCos rated UAS pilot verbal communication latencies to be as acceptable as those of conventional pilots. Because the overall traffic load within the sector was held constant, ATCos only performed slightly worse when multiple UAS were in their sector compared to when only one UAS was in the sector. Implications of these findings for UAS integration in the NAS are discussed.

UAS Contingency Management: The Effect of Different Procedures on ATC in Civil Airspace Operations: Lisa Fern, Conrad Rorie, Jay Shively; Published June 2014

UAS currently lack key capabilities required to routinely integrate with the current Air Traffic Management (ATM) system, including standardized and predictable procedures for managing off nominal or contingency events, especially those that are specifically related to UAS and their unique communications architecture [i.e., loss of the command and control communications link(s). A simulation experiment was conducted to examine the effects of a variety of currently-employed UAS contingency procedures on sector safety and efficiency, and Air Traffic Controller (ATC) workload. ATC participants were tasked with maintaining safe separation standards in a busy Terminal Radar Approach Control (TRACON) sector that included a single UAS. During different trials, the UAS would execute one of five contingency types, including one trial with no contingency (i.e., baseline), three different contingency procedures for the loss of command and control link, and one emergency landing procedure. Objective aircraft separation and sector throughput data, workload ratings, situation awareness ratings, and subjective ratings regarding the safety and efficiency of UAS operations in the NAS were collected. Results indicated that the simulated UAS contingency procedures had no significant impact on objective measures of safety and efficiency compared to the baseline. Further, there were no significant differences in subjective workload and situation awareness ratings between the baseline and any of the contingency procedures.

Unmanned Aircraft System Response to Air Traffic Control Clearances: Measured Response: Robert J. Shively, Kim-Phuong L. Vu, Timothy J. Buker; Published October 2013

Abstract: Successful integration of UAS in the NAS will require that UAS interactions with the air traffic management system be similar to interactions between manned aircraft and air traffic management. For example, UAS response times to air traffic controller (ATCo) clearances should be equivalent to those that are currently found to be acceptable with manned aircraft. Prior studies have examined communication delays with manned aircraft. Unfortunately, there is no analogous body of research for UAS. The goal of the present study was to determine how UAS pilot communication and execution delays affect ATCos' acceptability ratings of UAS pilot responses when the UAS is operating in the NAS. Eight radar-certified controllers managed traffic in a modified ZLA sector with one UAS flying in it. In separate scenarios, the UAS pilot verbal communication and execution delays were either short (1.5 s) or long (5 s) and either constant or variable. The ATCo acceptability of UAS pilot communication and execution delays were measured subjectively via post trial ratings. UAS verbal pilot communication delay, were rated as acceptable 92% of the time
when the delay was short. This acceptability level decreased to 64% when the delay was long. UAS pilot execution delay had less of an influence on ATCo acceptability ratings in the present stimulation. Implications of these findings for UAS in the NAS integration are discussed.

*Influence of UAS Pilot Communication and Execution Delay on Controller's Acceptability Ratings of UAS-ATC Interactions: Kim-Phuong L. Vu, Gregory Morales, Dan Chiappe, Thomas Z. Strybe, Vernol Battiste, Jay Shively, Timothy Buker; Published September 2013*

Abstract: Successful integration of UAS in the NAS will require that UAS interactions with the air traffic management system be similar to interactions between manned aircraft and air traffic management. For example, UAS response times to air traffic controller (ATCo) clearances should be equivalent to those that are currently found to be acceptable with manned aircraft. Prior studies have examined communication delays with manned aircraft. Unfortunately, there is no analogous body of research for UAS. The goal of the present study was to determine how UAS pilot communication and execution delays affect ATCos' acceptability ratings of UAS pilot responses when the UAS is operating in the NAS. Eight radar-certified controllers managed traffic in a modified ZLA sector with one UAS flying in it. In separate scenarios, the UAS pilot verbal communication and execution delays were either short (1.5 s) or long (5 s) and either constant or variable. The ATCo acceptability of UAS pilot communication and execution delays were measured subjectively via post trial ratings. UAS verbal pilot communication delay, were rated as acceptable 92% of the time when the delay was short. This acceptability level decreased to 64% when the delay was long. UAS pilot execution delay had less of an influence on ATCo acceptability ratings in the present stimulation. Implications of these findings for UAS in the NAS integration are discussed.

*Human Factors Guidelines for UAS in the National Airspace System: Alan Hobbs, Robert J. Shively; Published August 2013*

Abstract: The ground control stations (GCS) of some UAS have been characterized by less-than-adequate human-system interfaces. In some cases, this may reflect a failure to apply an existing regulation or human factors standard. In other cases, the problem may indicate a lack of suitable guidance material. NASA is leading a community effort to develop recommendations for human factors guidelines for GCS to support routine beyond-line-of-sight UAS operations in the national airspace system (NAS). In contrast to regulations, guidelines are not mandatory requirements. However, by encapsulating solutions to identified problems or areas of risk, guidelines can pro-vide assistance to system developers, users and regulatory agencies. To be effective, guidelines must be relevant to a wide range of systems, must not be overly prescriptive, and must not impose premature standardization on evolving technologies. By assuming that a pilot will be responsible for each UAS operating in the NAS, and that the aircraft will be required to operate in a manner comparable to conventional-ly piloted aircraft, it is possible to identify a generic set of pilot tasks and the information, control and communication requirements needed to support those tasks. Areas where guidelines will be useful can then be identified, utilizing information from simulations, operational experience and the human factors literature. In developing guidelines, we recognize that existing regulatory and guidance material may already provide adequate
coverage of certain issues. In other cases, suitable guidelines may be found in existing military or industry human factors standards. In cases where appropriate existing standards cannot be identified, original guidelines will be proposed.

Abstract: The ground control stations (GCS) of some UAS have been characterized by less-than-adequate human-system interfaces. In some cases, this may reflect a failure to apply an existing regulation or human factors standard. In other cases, the problem may indicate a lack of suitable guidance material. NASA is leading a community effort to develop recommendations for human factors guidelines for GCS to support routine beyond-line-of-sight UAS operations in the national airspace system (NAS). In contrast to regulations, guidelines are not mandatory requirements. However, by encapsulating solutions to identified problems or areas of risk, guidelines can provide assistance to system developers, users and regulatory agencies. To be effective, guidelines must be relevant to a wide range of systems, must not be overly prescriptive, and must not impose premature standardization on evolving technologies. By assuming that a pilot will be responsible for each UAS operating in the NAS, and that the aircraft will be required to operate in a manner comparable to conventionally piloted aircraft, it is possible to identify a generic set of pilot tasks and the information, control and communication requirements needed to support those tasks. Areas where guidelines will be useful can then be identified, utilizing information from simulations, operational experience and the human factors literature. In developing guidelines, we recognize that existing regulatory and guidance material may already provide adequate coverage of certain issues. In other cases, suitable guidelines may be found in existing military or industry human factors standards. In cases where appropriate existing standards cannot be identified, original guidelines will be proposed.

_UAS Integration Into the NAS: An Examination of Baseline Compliance in the Current Airspace System:_ Lisa Fern, Caitlin Kenny, Robert J. Shively, Walter Johnson; Published October 2012

Abstract: As a result of the FAA Modernization and Reform Act of 2012, Unmanned Aerial Systems (UAS) are expected to be integrated into the National Airspace System (NAS) by 2015. Several human factors challenges need to be addressed before UAS can safely and routinely fly in the NAS with manned aircraft. Perhaps the most significant challenge is for the UAS to be non-disruptive to the air traffic management system. Another human factors challenge is how to provide UAS pilots with intuitive traffic information in order to support situation awareness (SA) of their airspace environment as well as a see-and-avoid capability comparable to manned aircraft so that a UAS pilot could safely maneuver the aircraft to maintain separation and collision avoidance if necessary. A simulation experiment was conducted to examine baseline compliance of UAS operations in the current airspace system. Researchers also examined the effects of introducing a Cockpit Situation Display (CSD) into a UAS Ground Control Station (GCS) on UAS pilot performance, workload and situation awareness while flying in a positively controlled sector. Pilots were tasked with conducting a highway patrol police mission with a Medium Altitude Long Endurance (MALE) UAS in L.A. Center airspace with two mission objectives: 1) to reroute the UAS when issued new instructions from their commander, and 2) to communicate with Air Traffic Control (ATC) to negotiate flight plan changes and respond to vectoring and altitude change instructions. Objective aircraft separation data, workload ratings, SA data, and subjective ratings regarding
UAS operations in the NAS were collected. Results indicate that UAS pilots were able to comply appropriately with ATC instructions. In addition, the introduction of the CSD improved pilot SA and reduced workload associated with UAS and ATC interactions.

**Command and Control**

NASA has several C2 projects underway:

*Control and Non-Payload Communications (CNPC) Prototype Radio - Generation 2 Security Flight Test Report*: Dennis Iannicca, James Mckim, David Stewart, Suresh Thadhani, Daniel Young; Published June 2015

Abstract: NASA Glenn Research Center (GRC), in cooperation with Rockwell Collins, is working to develop a prototype Control and Non-Payload Communications (CNPC) radio platform as part of NASA Integrated Systems Research Program’s (ISRP) Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) project. A primary focus of the project is to work with the Federal Aviation Administration (FAA) and industry standards bodies to build and demonstrate a safe, secure, and efficient CNPC architecture that can be used by industry to evaluate the feasibility of deploying a system using these technologies in an operational capacity. GRC has been working in conjunction with these groups to assess threats, identify security requirements, and to develop a system of standards-based security controls that can be applied to the GRC prototype CNPC architecture as a demonstration platform.

The proposed security controls were integrated into the GRC flight test system aboard our S-3B Viking surrogate aircraft and several network tests were conducted during a flight on November 15, 2014 to determine whether the controls were working properly within the flight environment. The flight test was also the first to integrate Robust Header Compression (ROHC) as a means of reducing the additional overhead introduced by the security controls and Mobile IPv6. The effort demonstrated the complete end-to-end secure CNPC link in a relevant flight environment.

*Control and Non-Payload Communications (CNPC) Prototype Radio – Generation 2 Security Architecture Lab Test Report*: Dennis Iannicca, James Mckim, David Stewart, Suresh Thadhani, Daniel Young; Published May 2015

Summary: NASA Glenn Research Center, in cooperation with Rockwell Collins, is working to develop a prototype Control and Non-Payload Communications (CNPC) radio platform as part of NASA Integrated Systems Research Program’s (ISRP) Unmanned Aircraft Systems (UAS) Integration in the National Airspace System (NAS) project. A primary focus of the project is to work with the FAA and industry standards bodies to build and demonstrate a safe, secure, and efficient CNPC architecture that can be used by industry to evaluate the feasibility of deploying a system using these technologies in an operational capacity. GRC has been working in conjunction with these groups to assess threats, identify security requirements, and to develop a system of standards-based security controls that can be applied to the current GRC prototype CNPC architecture as a demonstration platform.

The security controls were integrated into a lab test bed mock-up of the Mobile IPv6 architecture currently being used for NASA flight testing, and a series of network tests were conducted to evaluate the security overhead of the controls compared to the baseline CNPC link without any security. The aim of testing was to evaluate the performance impact of the
additional security control overhead when added to the Mobile IPv6 architecture in various modes of operation. The statistics collected included packet captures at points along the path to gauge packet size as the sample data traversed the CNPC network, round trip latency, jitter, and throughput. The effort involved a series of tests of the baseline link, a link with Robust Header Compression (ROHC) and without security controls, a link with security controls and without ROHC, and finally a link with both ROHC and security controls enabled. The effort demonstrated that ROHC is both desirable and necessary to offset the additional expected overhead of applying security controls to the CNPC link.

**Control and Non-Payload Communications (CNPC) Prototype Radio - Generation 2 Flight Test Report:** Joseph Ishac, Dennis Iannicca, Kurt Shalkhauser, Brian Kachmar; Published October 2014

Abstract: NASA Glenn Research Center conducted a series of flight tests for the purpose of evaluating air-to-ground communications links for future unmanned aircraft systems (UAS). The primary objective of the test effort was to evaluate the transition of the aircraft communications from one ground station to the next, and to monitor data flow during the "hand-off" event. To facilitate the testing, ground stations were installed at locations in Cleveland, Ohio and Albany, Ohio that each provides line-of-sight radio communications with an overflying aircraft. This report describes results from the flight tests including flight parameters, received signal strength measurements, data latency times, and performance observations for the air-to-ground channel.

**Control and Non-Payload Communications Generation 1 Prototype Radio Flight Test Report:** Kurt Shalkhauser, Daniel Young, Steven Bretmersky, Joseph A Ishac, Steven Walker, James H Griner, Brian Kachmar; Published October 2014

Unmanned aircraft (UA) represent a new capability that will provide a variety of services in the Government (public) and commercial (civil) aviation sectors. The growth of this potential industry has not yet been realized because of the lack of a common understanding of what is required to safely operate Unmanned Aircraft Systems in the National Airspace System (UAS in the NAS). The desire and ability to fly UA is of increasing urgency. The application of UA to perform national security, defense, scientific, and emergency management are driving the critical need for less restrictive access by UA to the NAS. Existing Federal Aviation Regulations, procedures, and technologies do not allow routine UA access to the NAS. Access to the NAS is hampered by challenges such as the lack of an onboard pilot to see and avoid other aircraft; the ability of a single pilot or operator to control multiple UA; the reliance on command and control (C2) links; the altitudes, speeds, and duration at which the aircraft fly; and the wide variation in UA size and performance. NASA is working with other Government agencies to provide solutions that reduce technical barriers and make access to the NAS routine. This goal will be accomplished through system-level integration of key concepts, technologies, or procedures and through demonstrations of these integrated capabilities in an operationally relevant environment. This project provides an opportunity to transition the acquired empirical data and knowledge to the Federal Aviation Administration and other stakeholders to help them define the requirements for routine UA access to the NAS. Radio communications channels for UA are currently managed through exceptions and use either Department of Defense frequencies for line-of-sight (LOS) and satellite-based communications links, low-power LOS links in amateur bands, or unlicensed.
Industrial/Scientific/Medical (ISM) frequencies. None of these frequency bands are designated for safety and regularity of flight. Only recently has radiofrequency (RF) spectrum been allocated by the International Telecommunications Union specifically for commercial UA C2, LOS communication (L-Band: 960 to 1164 MHz, and C-Band: 5030 to 5091 MHz). The safe and efficient integration of UA into the NAS requires the use of protected RF spectrum allocations and a new data communications system that is both secure and scalable to accommodate the potential growth of these new aircraft. Data communications for UA—referred to as control and non-payload communications (CNPC)—will be used to exchange information between a UA and a ground station (GS) to ensure safe, reliable, and effective UA flight operation. The focus of this effort is on validating and allocating new RF spectrum and data link communications to enable civil UA integration into the NAS. Through a cost-sharing cooperative agreement with Rockwell Collins, Inc., the NASA Glenn Research Center is exploring and performing the necessary development steps to realize a prototype UA CNPC system. These activities include investigating signal waveforms and access techniques, developing representative CNPC radio hardware, and executing relevant testing and validation activities. There is no intent to manufacture the CNPC end product, rather the goals are to study, demonstrate, and validate a typical CNPC system that will allow safe and efficient communications within the L-Band and C-Band spectrum allocations. The system is addressing initial "seed" requirements from RTCA, Inc., Special Committee 203 (SC-203) and is on a path to Federal Aviation Administration certification. This report provides results from the flight testing campaign of the Rockwell Collins Generation 1 prototype radio, referred hereafter as the "radio." The radio sets operate within the 960- to 977-MHz frequency band with both air and ground radios using identical hardware. Flight tests involved one aircraft and one GS. Results include discussion of aircraft flight paths and associated radio performance.

Small UAS Technologies

NASA currently has many activities in this area summarized in Appendix B.

**Small Unmanned Aircraft Systems Integration into the National Airspace System Visual-Line-of-Sight Human-in-the-Loop Experiment:** Anna Trujillo, Rania Ghatas, Raymon McAdaragh, Daniel Burdette, James Comstock, Lucas Hemplet, Hui Fan; Published February 2015

Abstract: As part of the Unmanned Aircraft Systems (UAS) in the National Airspace System (NAS) project, research on integrating small UAS (sUAS) into the NAS was underway by a human-systems integration (HSI) team at the NASA Langley Research Center. Minimal to no research has been conducted on the safe, effective, and efficient manner in which to integrate these aircraft into the NAS. sUAS are defined as aircraft weighing 55 pounds or less. The objective of this human system integration team was to build a UAS Ground Control Station (GCS) and to develop a research test-bed and database that provides data, proof of concept, and human factors guidelines for GCS operations in the NAS. The objectives of this experiment were to evaluate the effectiveness and safety of flying sUAS in Class D and Class G airspace utilizing manual control inputs and voice radio communications between the pilot, mission control, and air traffic control. The design of the experiment included three sets of GCS display configurations, in addition to a hand-held control unit. The three different display configurations were VLOS, VLOS + Primary Flight Display (PFD), and VLOS + PFD + Moving Map (Map). Test subject pilots had better situation awareness of their vehicle position, altitude, airspeed, location over the ground, and mission track using the Map display.
configuration. This configuration allowed the pilots to complete the mission objectives with less workload, at the expense of having better situation awareness of other aircraft. The subjects were better able to see other aircraft when using the VLOS display configuration. However, their mission performance, as well as their ability to aviate and navigate, was reduced compared to runs that included the PFD and Map displays.

Making the Case for New Research to Support the Integration of Small Unmanned Aircraft Systems into the National Airspace System: Raymon McAdaragh, James Comstock, Rania Ghatas, Daniel Burdette, Anna Trujillo; Published April 2014

Abstract: This paper describes the current state of sUAS regulation, their technical capabilities and the latest technologies that will allow for sUAS NAS integration. The research that is needed to demonstrate sUAS NAS integration capability is identified, and recommendations for conducting this necessary research are suggested.

UAS in the NAS: Survey Responses by ATC, Manned Aircraft Pilots, and UAS Pilots: James Comstock, Raymon McAdaragh, Rania Ghatas, Daniel Burdette, Anna Trujillo; Published April 2014

Abstract: NASA currently is working with industry and the Federal Aviation Administration (FAA) to establish future requirements for Unmanned Aircraft Systems (UAS) flying in the National Airspace System (NAS). To work these issues NASA has established a multi-center "UAS Integration in the NAS" project. In order to establish Ground Control Station requirements for UAS, the perspective of each of the major players in NAS operations was desired. Three on-line surveys were administered that focused on Air Traffic Controllers (ATC), pilots of manned aircraft, and pilots of UAS. Follow-up telephone interviews were conducted with some survey respondents. The survey questions addressed UAS control, navigation, and communications from the perspective of small and large unmanned aircraft. Questions also addressed issues of UAS equipage, especially with regard to sense and avoid capabilities. From the civilian ATC and military ATC perspectives, of particular interest are how mixed operations (manned / UAS) have worked in the past and the role of aircraft equipage. Knowledge gained from this information is expected to assist the NASA UAS Integration in the NAS project in directing research foci thus assisting the FAA in the development of rules, regulations, and policies related to UAS in the NAS.
APPENDIX B: AN ASSESSMENT OF ODM DEMAND ESTIMATION

B.1: Estimating Travel Mode Split

B.1.1: Background

Modal split analysis between any mode and travel by air has never been a priority topic in transportation research. In the annual Transportation Research conference held in Washington DC every January, typically over 10,000 papers are offered either as in-person presentations or individual posters. In one conference attended a few years ago, less than 20 considered topics relevant to travel by air. The analysis of mode split between automobile and aircraft has never been a major transportation issue. But the emergence of electric air vehicles as a potential mode of travel within urban areas will change that. The key question at this phase of this emergence is how shall the demand for auto vs. air be measured and estimated. We now address this complex question.

Travel is, in general, a derived demand. Very few people travel for the sake of the trip itself. Most people do so to get to some other location to undertake some activity. For example, driving to the beach for a swim, or to the store go get some groceries, or flying to another city to visit a relative. Because it a derived demand, it is very difficult characterize the demand for travel with the same context used for the analysis of supply and demand in classical economics. What is the equilibrium point between the supply cost of a travel option and willingness-to-pay by the traveler? Does it depend on the purpose of the trip, that is, why you are going to the destination from where you are now? In fact, there is a strong argument that travel as an economic entity is empty core (see Button [1]). By this is meant that there is no point of intersection between the cost-demand curve for travel and the cost-supply curve, and therefore there is no value for which both supplier and users are satisfied.

Another economic factor that emerges as an important aspect of travel mode is its so-called utility value. Since travel itself is very, very rarely the purpose of a trip, the utility associated with a particular journey is always assumed to be negative. In other words, it always costs something to travel, and there is never any net benefit generated by a travel mode (provided you do not work in the travel industry).

Because of this lack of classical economic foundation, in the 1970’s and 80’s an alternative methodology emerged for estimating the choice of travel mode for a chosen trip. Note that this is different from estimating the demand for travel. The problem here is not how many trips will be made, but rather of all those expected trips, how many will be made using a specified method of travel. There is significant evidence that there are three primary factors of a travel choice that are important to the individual making the trip. 1) How much does it cost, in money, to make the trip using a specific mode? 2) How much time is required to make the trip using a specific mode? 3) What, if any, are the opportunities for useful or enjoyable activities while aboard the vehicle during the trip? How important each of these factors are depends on the individual making the trip and the purpose of the trip. For a journey to mourn the passing of a loved one, an individual may well consider time as much more important than money or the on-journey activities, while that same individual may reverse that position for a business trip to serve the needs of his small business, and change the relative factor values yet again when contemplating a vacation with his family.
In its simplest form, we can define the utility $U(j)$ of a specific travel option indicated with the notation $j$ as a straightforward linear equation:

$$U(j) = \beta_c c(j) + \beta_t t(j) + \beta_a a(j).$$

Here, the $\beta_c$ represents the value of the cost of travel option $j$, denoted as $c(j)$, $\beta_t$ the value of the time used by option $j$, denoted as $t(j)$, and $\beta_a$ the value of the in-journey activity set associated with option $j$, $a(j)$.

Then, if we have $J$ travel choices, we can compute the utility for each and the choice by an individual would be the option with the highest utility, as computed by the equation above. That is, the choice is option $k$ such that

$$U(k) = \max_{j \in J} \{\beta_c c(j) + \beta_t t(j) + \beta_a a(j)\}.$$

Simple enough? Well, not quite! There are several tacit assumptions in this formulations that yield incorrect results, and which must be accounted for if the model of travel choice implied here is to be empirically sound. And that makes the estimation of travel mode demand so difficult.

**B.1.2: The Logit Model**

The first, and perhaps most important, tacit assumption is that the three-term utility formulation above, or any other mathematical description of the utility of travel options, is complete, with no missing components or concepts that could alter the value of $U$ for a specific option. In other words, there is no aspect of the utility of any option to an individual that is not accurately expressed by the associated definition of $U$.

And in the context of NASA and its engineering background and history, that assumption is often a safe one, since the engineering associated with air and space travel have long had a compelling requirement for accuracy, given the overwhelming danger associated with air travel considerations bounded by unknown phenomena. Indeed, for air travel, there is every effort to minimize the unknowns related to the actual movement of the aircraft and its human control.

However, asserting that the definition of utility is complete as expressed above does not stand up to available empirical evidence. There are always elements of the trip that are not included in the utility definition. To address this incompleteness, the definition is extended to include another term. That is, $U(j)$ is redefined to be

$$U(j) = \beta_c c(j) + \beta_t t(j) + \beta_a a(j) + \epsilon.$$

The added term is $\epsilon$. It represents the unknown component of the computation of the utility associated with option $j$, and is a quantity that is governed by a known probability distribution. That structure then creates an alternative quantification of the estimated utility by describing a
range of values, each with an assigned probability, as opposed to a single value with unknown probability.

This is vital to understand. Knowing the utility an individual, any individual, assigns to a specific option is not possible, since we can never understand all the ramifications that individual carries around in his head when determining that utility. (See Sapolsky [2] for a worthy discussion of this impossibility.) Therefore, the best we can do is figure out the probability that a given individual will determine the utility to be in some range of values. We can do no better than that.

There is no universally acknowledged form for the probability distribution which describes $\epsilon$. Research into this continues, even after several decades. However, in the absence of any information to the contrary, two distribution forms are generally used for most choice descriptions.

Because of the similarity to linear regression, the obvious choice is that $\epsilon$ is distributed as a Normal (Gaussian) probability distribution with mean 0 and standard deviation $\sigma$. That is

$$
Pr[a \leq \epsilon \leq b] = \frac{1}{\sigma \sqrt{2\pi}} \int_a^b e^{-\frac{1}{2} \left( \frac{x}{\sigma} \right)^2} \, dx
$$

This hypothesis is often satisfied under the assumptions supporting the Central Limit Theorem, an essential fundamental concept of probability theory.

However, moving from this probability function to computing the probability of choosing a specific alternative from a (finite) set of available alternatives has proven to be extraordinarily difficult. Therefore, an alternative distribution structure, the assumptions of which are often met by a variety of utility models, is this function:

$$
Pr[a \leq \epsilon \leq b] = \int_a^b \mu e^{-(x-\eta)} e^{-e^{\eta-(x-\eta)}} \, dx.
$$

This distribution is called the Extreme Value Type I (EV1) distribution or, more traditionally, the Gumbel distribution. If the EV1 distribution can be empirically confirmed as valid for a specified utility, then we have the essential equality

$$
Pr[\text{option } j \text{ is chosen}] = \frac{e^{U(j)}}{\sum_{i=1}^J e^{U(i)}} = \frac{e^{\beta U\epsilon(j) + \beta U(j) + \beta_\omega(j)}}{\sum_{i=1}^J e^{\beta U\epsilon(i) + \beta U(i) + \beta_\omega(i)}}.
$$

This allows us to substitute a probability for a ranking. Rather than assume the individual will always choose the option with the highest utility, it assigns a probability to each option. That probability can then be used to estimate the proportion of the travel demand that will use each available travel option. Alternatively, it can be used to estimate how often a specific individual will select each of set of choices. The properties of the EV1 distribution are succinctly described in Ben Akiva and Lerman [3].
When the probability distribution of $\varepsilon$ is a Normal, the model is referred to as a *probit* model, and when it is the EV1 distribution it is called a *logit* model (pronounced low-jit). It was originally developed by Dan McFadden in the early 1970’s as the mode split model to estimate the use of rapid transit in the San Francisco bay area before BART was constructed. It is one of the most famous analyses ever done of transportation demand, perhaps because it was amazingly accurate. The original estimates were calculated in 1972, and in 1977 in a presentation by Dr. McFadden the estimates were compared to actual BART ridership. The estimate was within 2.7% of the observed demand. Dr. McFadden was awarded the Nobel Prize for his work in 2002.

The use of the logit has become widespread in transportation, marketing, medicine, ecology and several other fields. It is the primary distribution structure used in what is called Discrete Choice Theory. It can be applied to any problem where the subject of study is the selection of one (or more) choices from a finite or countable set. The (relatively) simple EV1 distribution has been extended in in several directions, including so-called nested logit functions, where some of the options are related to one another in separate ways and hence the probabilities are altered, and mixed logit structures, where additional aspects of the decision context are represented.

**B.1.3: Logit Models in Air Transportation Demand Analysis**

The current NASA estimates of intra-urban ODM aircraft demand stem from work done by the Virginia Tech University Air Transportation Systems Laboratory [4]. They use a very simple logit formulation to determine the probability of an urban commuter selecting an ODM service for her commute to school or work. (In the reference cited above, the model is called a C-Logit Model, short for Conditional Logit. The phrase is somewhat outdated, however.)

This analysis considers only commuter travel. For daily commuting, it is assumed that users have three transportation mode alternatives to choose from: auto, public transit, and air transportation based on ODM commuter aircraft. The utility function is estimated using two variables: total travel time and travel cost. The total travel time is estimated by calculating in-vehicle travel time and out-of-vehicle travel time. The value of out-of-vehicle travel time depends on the intermodal travel time from a population center to the ODM landing site. The C-Logit utility model looks like this:

\[
U(j) = \beta_c c(j) + \beta_t t(j) + \varepsilon
\]

where option $j$ is either private automobile, public transit, or ODM commuter aircraft.

The probability of selecting one of the three modes of transportation is estimated with this simple equation:

\[
\Pr[\text{selecting } j] = \frac{\exp[\beta_c c(j) + \beta_t t(j)]}{\sum_{k=1} \exp[\beta_c c(k) + \beta_t t(k)]}.
\]
Travel times and travel costs are estimated for any number of origin-destination pairs associated with observed commuting patterns, and the census tract as the smallest population geographic area for which potential ODM demand was calculated. The calibration of the C-Logit model involves generating coefficients $\beta_c$ and $\beta_t$. Once these two parameters have been estimated, then the share of the travel market for the three options can be easily calculated by simply computing the expected number of trips on each mode. That is, if $D$ is the total number of trips expected (for some fixed span of time), and $D(j)$ is the number expected to take mode $j$, then

$$D(j) = D \Pr[selecting \ j] = \frac{D \exp[\beta_c c(j) + \beta_t t(j)]}{\sum_{k=1}^{3} \exp[\beta_c c(k) + \beta_t t(k)]}.$$ 

However, implicit in this formulation is the key assumption that the values of the two parameters are the same for every individual in the set of people making the trip. But, there is overwhelming empirical evidence that different people have different parameter values, no matter what the alternatives are, so the equation for the probability of choosing a specific mode must be tailored to each specific individual in the marketplace. That is, we must write

$$\Pr[individual \ i \ selecting \ option \ j] = \frac{\exp[\beta_c (i) c(j) + \beta_t (i) t(j)]}{\sum_{k=1}^{3} \exp[\beta_c (i) c(k) + \beta_t (i) t(k)]}.$$ 

As we shall see, this complicates matters substantially.

**B.1.4: The AirMarkets Mixed Logit Model**

Thus, there is a fundamental relationship between the parameters of any utility function and the behavior that is represented by that function. And that relationship can quickly become very complicated as the representation of the interaction of important components of behavior become more essential to understanding how travel modes are chosen.

As an example of how a logit model can be enhanced to accommodate a varied population originating the demand, consider the model used by AirMarkets to represent the choice of fare class and itinerary for air service in a specific market. The utility function used for a travel party denoted with the indicator $i$ is given by the following equation for $U(i, j | \tau(i))$, the utility estimate of travel group $i$ for fare class itinerary $j$, given ideal departure/arrival time $\tau$ for travel party $i$:

$$U(i, j | \tau(i)) = -\beta_f (i) \ln f(j) + d(j) \left[-\beta_{\text{air}} (i) - \beta_{\text{it}} (i) \ln d_{\text{base}}, -\beta_{\text{air}} (i) N_{\text{air}} (j) - \beta_{\text{it}} (i) N_{\text{it}} (j) \right] + \beta_{\text{it}} (i) X_{\text{it}} (j) - \beta_{\text{air}} (i) X_{\text{air}} (j) + G(\tau(i) - t(j)) + \sum_{a \in \Psi} \left\{ I(a) \left[ \beta_{\psi} (a, i) + \beta_f (i) F(a, i) \right] \right\}$$
First, notice that all the $\beta$ parameters are specific to a given travel party indicated by the $i$. More on this below. The of independent variables related to the fare class and itinerary $j$ are:

- $f(j)$ is the fare (in 2015 US dollars) of the itinerary fare class $j$, and $\ln f(j)$ is the natural log of that fare. Natural log is a better fit, reflecting the fact that the impact of a $100$ fare increase on a base fare of $1000$ is perceived differently than on a base fare of $100$.
- $d(j)$ is the duration of the trip using $j$.
- $d_{base}$ is the base (shortest) duration of all the available itineraries known to the traveler. The base duration arises in the formulation because the individual is considered to compare a given itinerary with the best available itinerary, which, ceteris paribus, is the alternative with the shortest travel time.
- $N_{dc}(j)$ is the number of direct connections between aircraft of the same airline or airlines in the same alliance in itinerary $j$.
- $N_{ic}(j)$ is the number of indirect connections between aircraft of different, unassociated airlines in itinerary $j$. Indirect connections are considered less convenient, and hence have lower utility, than direct connections.
- $X_{1st}(j)$ is a dummy variable equal to one if the itinerary fare class uses the first-class cabin on the aircraft, and zero otherwise.
- $X_{ec}(j)$ is a dummy variable equal to one if the fare class uses the main cabin $X_{ec}(j)$ on the aircraft and zero otherwise. If both $X_{1st}(j)$ and $X_{ec}(j)$ are zero, then the business class cabin is assumed (the business cabin is the reference value for the indicator variables $X_{1st}(j)$ and $X_{ec}(j)$).

An air traveler can be either departure or arrival time sensitive. That is, the timing of a flight can be set by either when the traveler wants to leave for the destination, or arrive at the destination. Each time utility function has the same form, but different parameters. The function $G$ defines the time-of-day utility structure, and is given by a pair of Box-Cox transformations, one for early times and one for late times, which surround an interval of time about the ideal time called the indifference window, within which the traveler doesn’t have any time-related disutility. Specifically, the function $G$ is defined as

\[
G(\tau(i)-t(j)) = \begin{cases} 
\beta_E^G(i) \frac{(t(j)-\tau(i)-a+1)^{\beta_E}}{\lambda_E} - 1 & \tau(i)-t(j) < -a \\
0 & -a < \tau(i)-t(j) < b \\
\beta_L^G(i) \frac{(\tau(i)-t(j)-b+1)^{\beta_L}}{\lambda_L} - 1 & \tau(i)-t(j) > b 
\end{cases}
\]

where

- $\tau(i)$ is the ideal (departure/arrival) time for the travel party $i$.
- $t(j)$ the departure time of itinerary $j$.
- $\lambda_E$ and $\lambda_L$ are empirically derived parameters characterizing the Box-Cox representation of the utility curves for early itinerary departure/arrival times, respectively.
• $a$ and $b$ are the bounds of indifference window within which the traveler is indifferent to the itinerary departure/arrival time.

This specification thus stipulates that the disutility of not departing at the desired departure time (or, alternatively, arriving at the desired time) differs depending on if the actual departure/arrival time is before the desired (early) or after the desired (late). The indifference window reflects the fact that to some degree an air passenger doesn’t care if a flight is early or late. This expression and its derivation and estimation is described in detail in Parker and Walker [5].

The final terms in the utility depend explicitly on which airline is operating itinerary $j$. Let $\Psi$ be the set of all airlines operating in the market in question, and let the function $I(A,j)$ be an indicator variable which is one if $A \in \Psi$ operates itinerary $j$, and zero otherwise. The term $F(A,i)$ represents the frequent flyer mileage the traveler has with airline $A$. The inclusion of these last two variables in the utility equation make the utility function adaptive, in the sense that passengers with more experience with a specific carrier behave differently than those with less experience. The implications of this adaptivity to the passenger choice model are significant.

The various $\beta$’s are empirical coefficients for each individual in the represented by the demand in the market. These coefficients reflect the values assigned to the individual attributes of the itineraries by a specific traveler. The specific characteristic values associated with a given individual are determined by using a probability distribution that has been estimated from analysis of the incidence of each potential characteristic value found in the traveling population. How this was done, including the details of the research conducted to estimate the parameters of the relevant probability distributions, is discussed in Parker [6]. All the $\beta$ parameters except those associated with the $G$ function have a lognormal distribution. The parameters in the $G$ function have normal distributions. There are four sets of each of these parameters, one for each of the four travel variables consisting of trip purpose (business or leisure) and departure or arrival sensitivity.

With this utility function structure, the probabilities associated are of mixed logit form, with the mixing distribution being the distribution of ideal departure/arrival times in the population of that chosen market. That is, the probability of choosing $j$ from the set of available itinerary fare classes is given by the following:

\[ P(j) = \frac{1}{\sum_{k} e^{\sum_{i} \beta_i F(A,i) + \alpha_i}} \]

There is a good deal of research yet to be done on the relationship between a passenger’s itinerary preference and the airline operating the itinerary. Carriers have mixed opinions on the importance of cabin attendee attitude, on-time performance, cabin cleanliness, and other features of the flight experience directly under the control of the carrier. Incorporating such measures into a discrete choice model is also difficult, although item response theory through Rasch scaling (Fox and Bond [7], and von Davier and Carstensen [ref]) holds great promise in this regard.
where \([0, W]\) is a week time interval and \(\Theta(\tau)\) is the distribution of ideal departure/arrival times in the population over the period \([0, W]\). The distribution function \(\Theta(\tau)\) is estimated from empirical data.

In AirMarkets, the choice model described above is implemented in what’s called an Agent-Based Model, or ABM. This is a computer implementation which creates a synthetic population of travelers (actually, travelling groups), each with a specific set of \(\beta\) parameters for the four utility functions. The demand for a specific fare class in a specific market is then represented by the simulation of the choice of each agent representing the demand in that market. The synthetic population is created using the population probability distributions for the parameters that are the result of extensive, and ongoing research.

This also allows for the representation of the relationships between aspects of the parameter values. For example, Figure A.1 shows the empirical values of the fare utility parameter, the value of money \(\beta_f(i)\), and the value of the time utility parameter, the value of time \(\beta_d(i)\), for a collection of individuals from the survey from which the parameter values were estimated. Note that they are inversely related – the higher the value of time the lower the value of money. Also note that the relationship is quite strong, with a \(R^2\) value of 0.956 (the dotted line on the graph).

**Figure B.1: The Relationship Between Money and Time for Itinerary Choice**
These kinds of relationships are revealed extensively between the parameter values of any choice model, and need to be accounted for in the analysis of the probability of choice.

One recent extension to the AirMarkets demand utility is the inclusion of ODM service as a travel option in addition to scheduled service. This can be done by allowing the range of options to include service that has no scheduled departure or arrival times, is priced at ODM fare levels, and incorporates travel times consistent with current ODM aircraft. However, as shall be discussed below, extension to replication of ODM service in an intra-city context is yet to be accomplished.

It is easy to note the increased sophistication of the AirMarkets air travel model compared to the Virginia Tech model. Indeed, increased sophistication is a trait that has been evidenced in the application of logit models over the last five decades. There is a natural scientific requirement for parsimony when describing phenomena, and yet here we see significantly more descriptive detail. And even more detail is to be expected with future models. Such is the nature of modeling human choice behavior.

Returning to the idea that travel is a derived behavior, the reasons for doing it vary across an extremely broad range of activities. And the relevance of aspects of the travel – time, money, comfort – differ substantially according to the purpose of the trip and the disposition of the individuals making it.

As noted above, the AirMarkets model is an Agent-Based Model (ABM). An Agent-Based Model is a description of the behavior of each individual entity being active with respect to the phenomenon being studied. In this case, the model describes the behavior of each traveler independently of any other traveler, even though there is interaction between them, such as, for example, the sudden unavailability of a specific air travel itinerary because there are no longer any seats available on that flight.\(^{16}\) It is often referred to as a bottom-up model, since the primary focus of the description is the behavior of the smallest entity in a system. It is natural that an agent-based approach would be taken in the travel context, since the most complex aspect of the problem is the behavior of the individual travelers, and the agent orientation is the most direct way to represent that complexity.

\(^{16}\) That is not quite true. The agents represent not individual travelers, but groups that are traveling together. This is a key characteristic of any vehicular travel analysis, since the groups act as a single entity, but contribute more than one individual to the estimates of demand. It has little effect on the structure of the choice model, however.
Figure B.2: The Inherent Variation in ODM vs. Other Flight Choice

**B.1.5 Observed Inherent Variability**

The curve in Figure A.2 above is a representation of the underlying random effects caused by the discrete choice protocol resulting from the inherent variation in passenger itinerary choice. This is a graph of 480 simulation iterations of the demand for a specific ODM air service in a range of markets. The mean demand, as a proportion of the maximum possible market demand, is indicated by the heavy green vertical line. In addition, the thin green lines show the left and right 95% confidence interval values, also as a proportion of maximum demand. This is thus a picture of the inherent variation that can be expected in estimating air travel market demand under any circumstances. And the only variation shown here is the inherent variation that is left over after the explanatory descriptive value of the utility equation is accounted for.

And this level of inherent variation is seen throughout explorations of data empirically reflecting the demand for air travel. The data demonstrates the extreme variability of the observed demand values for a given market day after day. Figure A.3 is a graph of the daily observed demand on all carriers reported by the Airline Recording Corporation (ARC) for the market from Miami, Florida, to Seattle, Washington, USA for the calendar year 2005 [9]. The degree of variation is quite dramatic.
Some of the variation is, of course, due to the day of the week. But, as shown in Figure A.4, even within a specific day, there is extensive variation from week to week.\textsuperscript{17}

So even with a more sophisticated model of the choice behavior of passengers, there is still significant observed variation in that behavior. We haven’t eliminated it, but rather shown that our model cannot account for, and hence describe and accommodate it, even though is

\textsuperscript{17} The one Friday with the sharp drop happens to be the Fourth of July.
substantially more complex than the simple structure of the NASA model. Human behavior is a whole lot more complicated to model than we like to think! We now see that the layout of a model that describes mode choice for travel is inherently complex and ultimately stochastic in nature. Indeed, all empirical models of human behavior exemplify these two characteristics. And there is nothing we can do about it other than accept this reality, and accommodate it in our thinking.

B.1.6: The Frontier of Discrete Choice Modeling Technology.

More traditional models of disaggregate decision-making (like the AirMarkets choice model) have long ignored the question of why we want what we want. Human needs have been treated as given, and attention has largely centered on the expression of these needs in terms of choice behavior. Therefore, traditional models of choice decisions have focused on observable variables, such as option attributes, socioeconomic characteristics of the chooser, available information and past experience, as determinants of choice, at the expense of the biological, psychological and sociological reasons underlying the formation of individual preferences [10]. This idealized representation of travelers as optimizing black boxes with predetermined wants and needs is at odds with results from the social sciences. These studies have consistently shown that latent constructs such as attitudes, norms, perceptions, affects and beliefs can often override the influence of observable variables on disaggregate behavior.

The modeling methods associated with discrete choice are expanding into more generalized constructs. Specifically, the models used to describe the characteristics of the individual making the choice have expanded significantly. In general, the concept of the Structural Equation Model (SEM) has entered the picture as the mechanism for creating in-depth descriptions of the underlying human behavior (see Westland [11] for an in-depth discussion). SEM has been around for a long time, but just recently has moved from a more-or-less psycho-sociological context into a much wider role, including extensive application in marketing (see the published works from the Academy of Marketing Science for literally dozens of examples).

One form is the so-called Integrated Choice and Latent Variable (ICLV) described by Walker and Vij [12]. The phrase “latent variable” refers the measurement of a driving force behind human behavior that is not directly observable, but is represented by one or more observable characteristics that are implied by that driver. For example, they attempt to explicitly model the cognitive processes that are the foundation of any choice context. These models allow for the identification of structural relationships between observable variables that could not be identified using choice models without latent variables, and parameter estimates from the ICLV model are shown to be potentially more efficient than equivalent estimates from other model structures.

ICLV models overcome some of these deficiencies. They were first put forth by McFadden [10] and expanded on by Ben-Akiva et al.[13]. Improvements in computational power and the estimation software such as Biogeme (Bierlaire [14]) have since created a broad expansion of the use of these tools. In the context of transportation, ICLV models have been applied to the study of travel mode choice (Paulssen et al., [15]), and route choice (Prato et al., [16]) among many others.

In the general formulation, two components can be distinguished: a multinomial discrete choice model and a latent variable SEM. Each of these components consists of a structural and a measurement component. In the discrete choice component, the alternatives’ utilities may depend on both observed and latent attributes of the alternatives and characteristics of the decision makers.
Mathematically, such a model uses the following set of equations:

\[ U_n = BX_n + \Gamma X_n^* + \varepsilon_n \]
\[ X_n^* = AX_n + \nu_n \]
\[ i_n = DX_n + \eta_n \]
\[ y_{nj} = \begin{cases} 1 & \text{if } u_{nj} \geq u_{nj'} \text{ for } j',j \in \{1,\ldots,J\} \\ 0 & \text{otherwise} \end{cases} \]

In the first equation, \( U_n \) is the \( J \times 1 \) vector of utilities of each of the \( J \) alternatives, as perceived by decision-maker \( n \), \( X_n \) is the \( K \times 1 \) vector of observable explanatory variables, \( X_n^* \) is the \( M \times 1 \) vector of latent explanatory variables, \( B \) and \( \Gamma \) are the \( J \times K \) and \( J \times M \) matrices of model parameters denoting sensitivities to the observable and latent variables, respectively, and \( \varepsilon_n \) is the \( J \times 1 \) vector denoting the stochastic component of the utility specification.

The second and third equations together form an SEM. In them, \( A \) is the \( M \times K \) matrix of model parameters denoting the structural relationship between the latent and observable variables, and \( \nu_n \) is the \( M \times 1 \) vector denoting the stochastic component of that relationship. The third equation defines \( i_n \) as the \( R \times 1 \) vector of indicators used to measure the latent variables, \( D \) is the \( R \times M \) matrix of model parameters denoting the sensitivities of the measurement indicators to the latent variables, and \( \eta_n \) is the \( R \times 1 \) vector denoting the stochastic component of the measurement equation. Finally, the fourth equation just describes the observed choices where \( y_{nj} \) is the choice indicator, equal to one if decision maker \( n \) chose alternative \( j \), and zero otherwise.

Different assumptions about the structure of each of the stochastic variables can lead to different forms of the ICLV model. Currently, it is usually assumed that each element of \( \varepsilon \) is independently and identically distributed with an EV1 distribution across alternatives and agents, resulting in a multinomial logit kernel for the discrete choice model. Under this assumption, the probability that agent \( n \) chooses alternative \( j \) is of the following general form:

\[
\Pr[y_{nj} = 1 | x_n, x_n^*, B, \Gamma] = \frac{\exp(\beta_j^* x_n^* + \gamma_j^* x_n^*)}{\sum_{j'=1}^{J} \exp(\beta_{j'}^* x_n^* + \gamma_{j'}^* x_n^*)}
\]

where \( \beta_j^* \) and \( \gamma_j^* \) are the \( 1 \times K \) and \( 1 \times M \) vectors corresponding to the \( j \)th rows of \( B \) and \( \Gamma \), respectively.

This extension of the discrete choice model to include and SEM is a result of extensive computing capacity. As with many aspects of modern analysis, the ability of current computers to manipulate massive amounts of data creates the opportunity for all manner of the expressions of relationships. Such analytical sophistication (or so it looks) should enable us to be ever more specific and accurate making predictions about future behavior, and thus develop wiser and more efficacious public policies or private products related to dealing with the future.

But cautions are also in order. We shall discuss two: the first stems from the mathematical basis of SEM models, and the second the need for data in a context that does not now exist.

B.1.7: The Danger of SEM Models: The Stone-Weierstrass Theorem
Structural equation models have been around a long time, but only until recently have they become widespread, especially in the social sciences. One of the reasons behind their slow adoption across multiple disciplines is that they can be very difficult to estimate in any given situation. Before the development of the extensive computing capability now available, the personnel and operational cost of estimating the values in matrix $A$ when $M$ and $K$ were even of small size was prohibitive. Modern computing has changed all that. Now the solution of the matrix equation is readily found (assuming the data is available) in a matter of no more than a few hours with even hundreds or thousands of rows and columns in the matrix.

But that creates an alternative problem that needs to be recognized. It is based on a mathematical theorem called the Stone-Weierstrass Theorem. The Stone-Weierstrass Theorem was initially proved by Karl Weierstrass (1815-1897) in 1885. It was contemporaneously extended by the U. S. mathematician M. H. Stone to a far-reaching generalization. It is one of the most important theorems in all of advanced mathematics. For a technical discussion, see Hewitt and Stromberg ([17], pp 94-99). Formally, it states:

Let $X$ be a nonvoid compact Hausdorff space and $\mathbb{C}$ be a separating family of functions in the $n$-dimensional space $\mathcal{R}_n(X)$ containing the constant function $1$. Then the polynomials with real coefficients in functions from $\mathbb{C}$ are a dense sub-algebra of $\mathcal{R}_n(X)$ in the topology induced by the uniform metric.

Translated into English, what this says is that if you have an arbitrary set of points in an appropriate $n$-dimensional space made up of real numbers, then you can always find a finite set of polynomials that will approximate the points in the arbitrary set as closely as you like. More fluidly, any relationship represented by a set of numbers can be approximated as closely as you would like with a set of polynomials of those real numbers.

This means that you can observe a relationship between a set of phenomena and always find a set of polynomial equations that represents the relationship. And this is why SEM’s can be so valuable. They are the set of polynomials. But there is a downside that is fraught with concern: The polynomials represent nothing except mathematical constructs. They may not mean anything at all outside of the implications of Stone-Weierstrass. They may bear no relationship whatsoever with the underlying physical and behavioral properties of the phenomena being studied. That means that there needs to be arguments beyond the fit of the equations to the available data. To quote Sir Francis Crick, co-discoverer with Watson of the structure of DNA, “The only thing worse that theory without data is data without theory.”

B.2: Current Intra-City Transportation Planning

Transportation modeling on the intra-city scale has engaged the use of SEM’s for some time now. While there is no uniformly used method or model, various behavioral approaches have been addressed with a significant variety of useful results. There are several dozen, if not hundreds, of firms which offer variations on this general theme of behavioral models integrated with discrete choice stochastic structures.

Perhaps the most advanced methodologies are those akin to the AirMarkets agent-based structure. Because transportation is a derived demand, the activities of individuals determine the bases for the needs for transportation. Over a long distance, such as inter-city, the time and cost of transportation become key indicators of transport mode choice. But the purpose of the trip is usually restricted to a simple classification of business or personal, based on who is paying for the financial cost of the trip and for the time involved. When the travel takes an extensive amount of time and money, other aspects of the journey become less important. However, when the time and cost of the journey is relatively small, such as in an intra-city context, the trip purpose can become much more important. For example, the travel for a routine trip, such commuting to work or school, is often handled much differently than the
travel associated with a night on the town in a fancy restaurant followed by dancing in a night club. Thus, trip purpose is much more complex, and therefore modeling human behavioral characteristics take on significantly increased importance. This differentiation is possible with agent-based models, since activity representation of travelers are far easier to implement with agents.

The issue of travel mode choice is, of course, a core structural requirement for any urban transportation policy investigation. All cities have at least some form of mode choice. Almost everywhere in the world private automobiles are available in some form or other. And where there are private vehicles, there are forms of transportation that use such vehicles for public use, such as taxi services (including Uber, Lyft, etc.), tuktuks in India and Sri Lanka, jitney bus service in many countries, and various kinds of large-scale public transportation, including light rail, subways, elevated trains, and high-speed rail.

But one key option is rarely, if ever, found among the set of intra-urban transportation modes. And this is air travel within a city.

B.3: Modeling the Mode Split between Aircraft and Automobiles

So, the mode split model that needs to be used for intra-urban transport demand analysis cannot rely on empirical data describing existing mode choices available to travelers in a city – because there is none! And that presents the central problem with the analysis of air travel within a city.

There are two ways in which the data for any kind of discrete choice model can be assembled. We can observe the actual choices made by transport users along with their coincident behavioral properties. From this data, relatively simple maximum likelihood methods will yield a quite sophisticated model, including an SEM. It does not matter how sophisticated or complex the behavioral representation is. Such a model is often called a revealed preference model, since the selection of a specific option from a set of those available is revealed by subject behavior. To our knowledge, revealed preference is used whenever possible, since empirical data exists for both the independent variables (behavioral values) and dependent variables (the choice).

But if one of the options of interest does not exist, then the revealed preference approach is not suitable. And that is the case we have with intra-urban air travel. Data collection under these conditions require a different approach which is referred to in the discrete choice field as stated preference.

One of the world experts in stated preference theory is Jordan Louviere, now retired and living in Australia, where he chaired the Marketing Department at the University of Technology Sydney as well as consulted with many firms in the applications of stated preference discrete choice theory. His work is foundational, including the seminal work *Stated Choice Methods* produced with Hensher, a renowned transportation analyst, and Swait, an accomplished statistician [18]. Following his lead, the investigation of intra-city air travel will be stuck in middling generalities until a proper, formal logit model is developed using stated preference methods.

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18 Indeed, the only city we are aware of with available intra-city transportation is Sao Paulo, Brazil. Helicopter service between airports in New York and elsewhere is too restricted to be considered an available transport option for the general public.

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A stated preference survey is significantly different from the revealed preference case because it is necessary to describe the non-existent options in terms that are meaningful to the respondent. Furthermore, the descriptive parameters of the non-existent option structure must be designed to have ranges of values that are technically possible and describable. For example, data on intra-urban air travel options would include a description of the vehicle, means of access to it, its speed, its capacity, and its operating cost. In addition, these features would need to be translated into terms meaningful to potential customers, in contrast to engineering descriptions most often seen now. Finally, an extensive survey is usually necessary for stable results to be collected. The stated preference survey that supports the construction of the AirMarkets discrete choice model was created from a sample size of more than 12,000 responses.

References


