POINT-TO-POINT! VALIDATION OF THE SMALL AIRCRAFT TRANSPORTATION SYSTEM HIGHER VOLUME OPERATIONS CONCEPT

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Abstract

Described is the research process that NASA researchers used to validate the Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) concept. The four phase building-block validation and verification process included multiple elements ranging from formal analysis of HVO procedures to flight test, to full-system architecture prototype that was successfully shown to the public at the June 2005 SATS Technical Demonstration in Danville, VA. Presented are significant results of each of the four research phases that extend early results presented at ICAS 2004 [1]. HVO study results have been incorporated into the development of the Next Generation Air Transportation System (NGATS) vision [2] and offer a validated concept to provide a significant portion of the 3X capacity improvement sought after in the United States' National Airspace System (NAS).

1 Introduction

In the United States, the current National Airspace System (NAS) of hub and spoke operations has served its purpose well, but it is beginning to reach a capacity plateau. Due to increasing demand on the system and with only modest potential gains in the number of flights, the system could reach gridlock within the next 10-15 years [2,3]. Several new, small, efficient aircraft are being developed by Honda, Cessna, Diamond, Eclipse, Safire, Cirrus, Lancair, Adam Aircraft, and others to provide point-to-point service and make use of small airports, many without control towers that lie outside Air Traffic Control (ATC) radar coverage.

When instrument meteorological conditions restrict operations to instrument flight rules at non-towered, non-radar airports, ATC uses procedural separation that restricts operations to only one approaching or departing aircraft at a time – the "one-in/one-out" paradigm which severely limits the operational throughput at these airports. Air charter operators might be compelled to use these airfields if the operational efficiency, availability, and thereby accessibility can be improved. The Small Aircraft Transportation System (SATS) Project breaks the one-in/one-out paradigm and expands capacity by allowing multiple, simultaneous operations. The concept of operations (CONOPS) that achieves this goal is termed SATS "Higher Volume Operations" (HVO) [4,5].

SATS HVO was developed to address these issues. The validation process applied by the NASA research team included a number of activities aimed at increasing the technology readiness level from a visionary concept to proof-of-concept demonstration. Important stakeholders were kept in the loop throughout the validation process which continually obtained metrics that were important to the stakeholders.

2 SATS HVO CONOPS Overview [4, 5]

The SATS HVO concept is based on a distributed decision-making environment that assumes major decision-making responsibility be held by the pilot, and resource mitigation be held by ground-based automation, the airport management module (AMM). The concept utilizes a newly defined flight operations area called a Self-Controlled Area (SCA), established during instrument meteorological conditions around "SATS designated airports" (i.e., non-towered, non-radar airports). Within the SCA, pilots, using airborne systems, would have the ability and responsibility to maintain separation from other similarly equipped airplanes. Aircraft operating in this airspace would require: automatic dependent surveillance-broadcast (ADS-B), a two-way data link, and appropriate self-separation tools. The AMM provides sequencing information to the arriving aircraft. It distributes an arrival sequence and broadcasts the total number of arriving aircraft in the SCA. The AMM does not, however, provide separation, altitude assignments, or sequence departures.

2.1 Normal Operations

Aircraft will approach a SATS airport on an instrument flight rules clearance granted by ATC to a transition fix above the SCA. This fix is also an initial approach fix (IAF) for an instrument approach procedure. (GPS-T instrument approach procedures were chosen as a basis for this concept, although other instrument approach procedures could be used). Prior to reaching the fix, the pilot requests a landing assignment from the AMM through their onboard system. The AMM responds with the SCA entry procedure (standby, vertical or lateral), relative sequence information (follow <Callsign>), and missed approach hold fix assignment (e.g. ANNIE or CATHY). The AMM only sequences arrivals (including missed approach aircraft), not departures. Nominally, up to four arriving aircraft are allowed in the SCA before entry is denied (AMM issues a "standby"), though this constraint can be affected by local airspace restrictions. (The number of arriving aircraft, including those executing a missed approach, is limited by the holding altitudes available for the approach. Figure 1 shows the nominal approach design with four potential holding segments.)

Following entry assignments and the HVO procedure to "descend to lowest available altitude," pilots are deconflicted by the procedure from other arriving aircraft (i.e., the AMM reserves a slot at one of the IAFs for each SCA aircraft until it lands or departs the SCA).

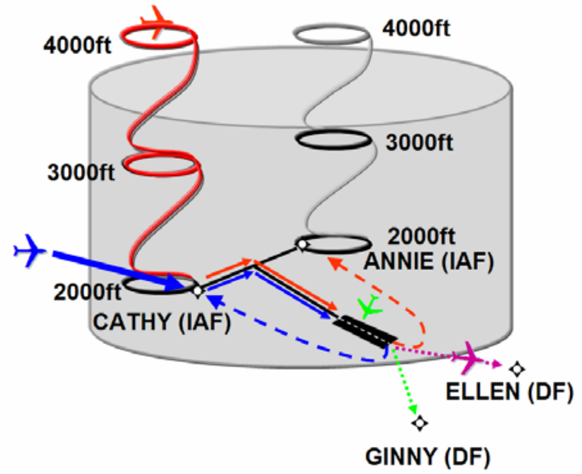

Fig. 1. SATS HVO Example

Many of the features of the GPS-T based SATS HVO concept are depicted in Figure 1. SATS arrivals (Red and Blue aircraft) to the IAFs with alternating missed approaches, and departures (Green and Purple aircraft) to the Departure Fixes (DFs):

- **Blue** – entering the SCA having coordinated descent with ATC when no other aircraft assigned to CATHY, missed approach is blue dashed path, AMM returned: "*LATERAL entry, follow NONE, missed approach CATHY,*"
- **Red** – having arrived by ATC instruction to transition fix above SCA at 4000ft with one other CATHY assignment, the AMM returned: "*Vertical entry , follow BLUE, missed approach ANNIE,*"
- **Purple** – departing SCA via departure procedure and contact ATC prior to DF,
- **Green** – released by ATC to depart (within departure window); holding short and using on-board tools to find open slot in arrival stream to take the runway and depart.

Pilots given a "standby" sequence can track the number of aircraft in the SCA to estimate their delay as they continue to their clearance limit, the transition fix at an altitude above the SCA, and hold. When the pilot receives an AMM entry message with sequence and missed approach information, the pilot checks for an available holding altitude, and will request descent from ATC. The pilot can then determine if further descent is prudent by following the "lowest available altitude" procedure at the IAF, (clearing for traffic below is the pilot's self-separation responsibility in the SCA). Pilots initiate their approach once adequate spacing behind the lead aircraft has been met (determined through either a generic rule-based spacing procedure, i.e., safe for all combinations of aircraft performance, or by using an on-board self-spacing tool). The AMM reserves a holding slot for assigned missed approaches. A pilot executing a missed approach climbs to the "lowest available altitude" at the missed approach holding fix and then gets a new arrival sequence.

For SATS departures, pilots will file flight plans with a SATS departure procedure to a departure fix (DF, i.e., Figure 1 ELLEN or GINNY). Just as in today's non-radar environment, the pilot should expect a clearance void time and potentially a release time restriction as part of their instrument flight rules clearance. This affords seamless integration with today's instrument flight operations. Within this ATC departure window, they will use on-board information/tools to deconflict themselves with landing traffic, e.g., ensure no arriving aircraft within 5nm of the airport. The pilot would then depart and contact ATC according to the departure procedure.

2.2 Off-Nominal Operations

Baxley et al [6] describe three categories of off-nominal situations that may occur in a future HVO environment: *routine*, such as a change of landing approach direction or pilot operational errors; *equipment malfunctions*, such as a loss of an aircraft's communication system; and *emergency situations*, such as a priority request for an emergency landing. They developed procedures to handle many of these situations.

Two of these procedures were tested in a piloted simulation study [7]: procedures to handle cancellation of approach requests with transitions to visual flight rules (VFR), and priority requests from approaching aircraft. Priority landing requests allow pilots to land ahead of others in the sequence. Cancellations of approach requests allow participating pilots to transition to a visual approach if desired. The choice of off-nominal procedures for this first study was based on the limited research resources, the expected likelihood of VFR transitions, the relative importance of priority landings, and their foreseen potential to influence the tenets of HVO.

3 Validating the HVO Concept

The NASA SATS HVO research team developed and applied a four phase process to design and validate the HVO concept, depicted in Figure 2. The HVO team addressed one of four operating capabilities the SATS Program was responsible to research and develop. Due to limited resources and an aggressive schedule, the HVO team had to prioritize and select research areas which would have the greatest and most lasting impact. Although the arrows in the diagram point to work being done sequentially, much was done in parallel, with each team member leading a portion of the overall research. The crossed arrows show how lessons from one research phase were applied to the others through continuous feedback.

The "HVO concept model," was created and documented as the SATS HVO CONOPS [5] in phase one. In phase two, an HVO computer model simulation environment was developed and verified. Phase three, "human-in-the-loop (HITL) concept model validation," focused on determining if HVO functionality and procedures were safe, flyable and acceptable to pilots and controllers. Phase four validated earlier simulation results through a proof-of-concept public demonstration of HVO. Again, each of the phases provided feedback into the others.

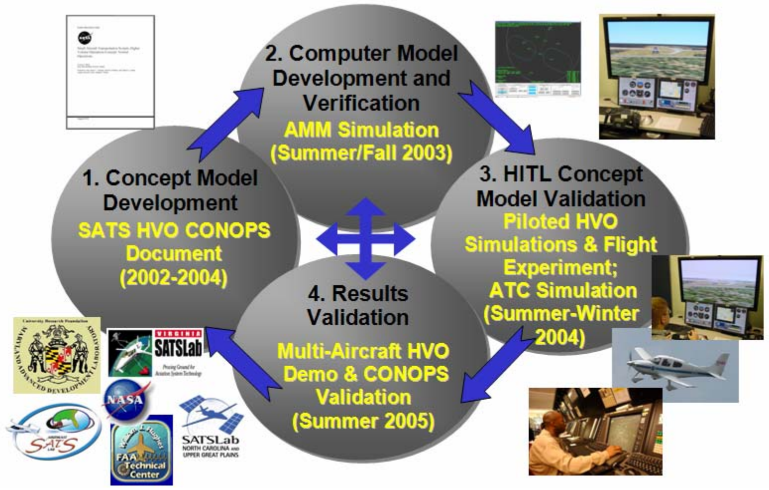

Fig. 2. HVO Validation

4 Phase One: Concept Development

The HVO concept was developed by a dedicated NASA research design team from a clean slate. Air traffic controllers generally have viewed today's one-in-one-out IFR procedures about these small airports as a nuisance operation to manage so generally welcomed a system with better procedures. "Better" meant HVO had to be a usable system, which was simple to control and provided better throughput with less workload. Pilots also welcomed a solution to the problem of having to hold in IFR waiting their turn. Solving this problem meant the team incorporated inputs of procedure designers, system engineers, human factors researchers, pilots and air traffic controllers. Concept iterations took three years through hundreds of dedicated team engineering and design sessions, consultations with outside stakeholders and implementers. After defining the concept for normal operations, off-nominal operations were also defined [6].

4.1 HVO Design Constraints

Several shaping constraints limited the scope of HVO concept development. HVO procedures and technologies were designed to be integrated into the NAS by 2010. This limitation prohibited new technology from being developed, so the team chose to integrate several state-of-the-art technologies, thus increasing the likelihood of 2010 certification. Fielding aircraft equipped for HVO would be based on an economic benefit case that such equipage would increase airport access and operational capacity during low visibility conditions. To increase the likelihood of system certification, HVO was also designed with simplicity in mind. HVO flight procedures had to be a logical evolution of today's IFR procedures for controllers and pilots, and use cockpit traffic displays and communications, navigation and surveillance (CNS) systems being fielded today in emerging very light jet (VLJ) aircraft. The HVO design also had to attempt to minimize pilot and controller workload, and integrate with today's en-route ATC environment.

4.2 Formal Methods Analysis [8, 9]

A Formal Methods analysis was conducted in parallel with the HVO CONOPS development to verify safety of HVO [8,9]. The main contribution of this work is the formal assurance that under all possible arrival and departure sequences, key safety properties hold for the HVO CONOPS while capacity benefits are preserved. During this analysis, the key safety properties of the HVO concept were established by mathematical verification methods based on formal logic and theorem proving. HVO was modeled by using non-deterministic, asynchronous mathematical models of the operational concept. This study found that HVO procedures are safe, that self-separation can be maintained when pilots adhere to the HVO procedures (including AMM sequencing and logic) and that there are no procedural deadlocks (all aircraft in the SCA eventually land or depart). Recommendations from an initial study were incorporated into the HVO concept and made it more robust, the most important being improved HVO missed approach procedures.

4.3 HVO Throughput

The capacity benefits of SATS are key to the concept. Using NASA's HVO simulation batch mode, multiple runs were investigated for both today's procedures (Baseline) and the HVO concept, using an equal number of arriving and departing aircraft per hour from multiple routes with varying approach speeds. These Monte Carlo batch studies indicate the throughput of the HVO concept results in a three to five-fold increase in the rate of flight operations [1, 11]. The metrics sought were the arrival delays incurred by increasing traffic counts (operations equate to 50% arrivals and departures). Both arrivals and departures needed to be considered together for accurate system modeling. The key points beyond which arrival delays begin to grow in an unstable manner are at 8 operations per hour for the Baseline, and 24 operations per hour for HVO procedures. These batch analyses are described in more detail in [11] and closely correlate with the results of the January 2005 linked NASA – FAA controller validation experiment [12].

4.4 HVO Conflict Prevention Design [13]

Figure 3 illustrates that inherent in the design of HVO is a multilayer methodology to explicitly prevent loss of separation conflicts between aircraft [13].

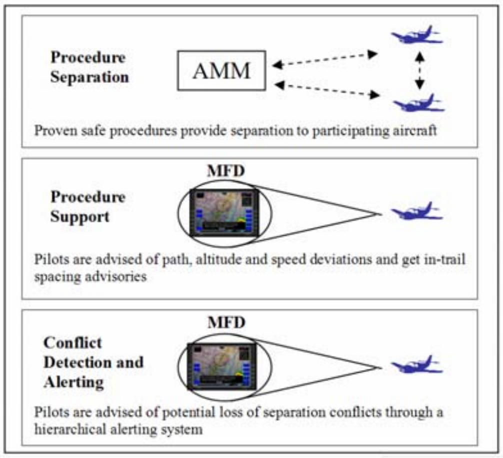

Fig. 3. HVO Conflict Prevention Design

Aircraft participating in HVO must adhere to procedures and rely on onboard automation. Recall from the Formal Methods analysis that adhering to simple and robust HVO flight procedures will ensure aircraft-to-aircraft separation is maintained. The multilayer system gives pilots support and guidance during the execution of normal operations and advance warning in case of procedure deviations or off-nominal operations.

Adherence to HVO arrival and departure procedures represents the first of this multilayer method. A second layer is provided by the procedure support automation that includes onboard conformance monitoring, approach spacing and altitude determination tools. The conformance monitoring tool advises pilots of altitude, speed and path deviations during all approach segments and holding patterns. The spacing tool provides in-trail spacing advisories and approach initiation time. The altitude determination tool identifies open holding altitudes within the SCA. All procedure support advisories are shown in the form of dynamic messaging on the experimental MFD [14]. The third layer in the conflict prevention strategy is provided by the Conflict Detection and Alerting (CD&A) logic which is also part of the onboard automation. To address cases of procedure deviations or off-nominal conditions, a CD&A method was developed that uses a combination of state vector and procedure-based intent for conflict detection and a multistage, asymmetrical alerting system. The three layers are logically independent.

5 Phase Two: HVO Computer Model Development

In parallel with the development of the HVO CONOPS, NASA also led the development of a simulation environment in the Air Traffic Operations Lab (ATOL) at NASA Langley. This computer model represented HVO airports, the AMM, and multiple linked general aviation (GA) simulators with HVO interface functionality incorporated into the cockpit avionics and displays. Modeling the HVO CONOPS as it was being developed was a significant team resource challenge, but led to a broad and cohesive team and simulation capability. The AMM was the key HVO system developed in this phase, and became resident for logic testing through operational scenarios. A spiral build construct was continuously applied which enabled progressive improvements to the simulation platform, culminating with a build capable of supporting phase three multi-aircraft pilot-in-the-loop validation testing of HVO.

5.1 Elements of Preliminary Configurations

The HVO CONOPS team and developers possessed much experience with the Advanced Air Transportation Technologies Distributed Air-Ground Traffic Management (AATT DAG-TM) Project, especially as it was implemented in the ATOL. Early considerations for defining HVO flight procedures included en route tools and cockpit displays. These included 4D path assignments and projections, required time of arrivals (RTAs) to IAFs, conflict detection, prevention and resolution systems that were designed for large airliners with complex avionics including flight management computer systems (FMCS). These concepts and systems served as an excellent simulation platform starting point, but eventually were modified or replaced.

5.1.1 Simplifying the Design

Along with aircraft sequence, RTAs to the IAF were initially issued by the AMM. To soften the controlling element of issuing an RTA into an advisory level of notification, the concept of an ReTA, requested time of arrival, was developed. It soon became apparent that the sequence alone should be sent from the AMM with pilots assuming responsibility for spacing in the SCA enabled by flight procedures (that assured deconfliction from other aircraft). Hence, the AMM became simpler because the time component was eliminated.

5.1.2 HVO Conflict Prevention Development

As mentioned previously, HVO has a multi-tiered conflict prevention system consisting of procedural separation, procedure support, and CD&A. Tradeoffs were considered to create a conflict prevention system that better fit the stricter navigation requirements of the terminal approach path, evolved from conflict prevention in the en route flight path environment. The traffic density in the terminal environment also requires shorter look-ahead times and flight path intent information be broadcast to lessen nuisance traffic alerting.

5.1.3 The HVO Pilot Interface

In designing the pilot interface for HVO HITL evaluations, the flight platform available for eventual flight test was the NASA Langley Cirrus SR22 with a large Avidyne® MFD. Figure 4 shows the general aviation simulator and the Cirrus SR22's instrument panel used for the experiments. Common software across platforms was developed to drive the MFD [14] and the Horizontal Situation Indicator (HSI) displays. Variation between the simulation and flight profiles was deliberately minimized so as not to alter experimental objectives or hypotheses. Pilots were tasked to manually fly scenarios in simulated instrument meteorological conditions using traditional round-dial instruments for primary flight guidance information (i.e., without autopilot). Pilots were tasked to meet FAA instrument rating practical test standards criteria during all scenarios [15]. Another research postulate not tested was that if pilots performed HVO tasks well with the simple NASA Cirrus SR22 research avionics configuration, then better avionics (e.g., a primary flight display) might simplify tasks even further [16-18].

Fig. 4. HVO Experiment Platform Progression (note commonality of HSI and MFD)

5.2 AMM Verification

The AMM function and associated algorithms were verified and validated using a representative set of normal HVO scenarios, i.e., flown to procedure without deviations. Each of the AMM logic rules was put to test and because of the formal methods evaluation of HVO, redesigns were minimal and the AMM was readied for HITL studies. After the normal studies were completed, the AMM was modified to accept a priority landing request (in flight emergency situation) and re-sequence aircraft within the SCA according to an expanded logic set. Verification of the new AMM was also done by scenario testing and eventually used in another HITL evaluation [20].

6 Phase Three: HITL Concept Model Validation [1, 10, 12, 16-20]

The HVO CONOPS (concept model) was validated through piloted simulation, flight experiment, and air traffic controller simulation studies. Human-in-the-loop scenarios were developed that compared SATS HVO to the one-in-one-out procedural control environment available today (Baseline). Key experimental objectives were to answer these two questions:

- “Can pilots safely and proficiently fly an airplane while performing HVO procedures?”
- “Do pilots perceive that workload while performing the HVO procedures is no greater than flying in today’s system?”

Low-time instrument rated evaluation pilots provided experimental data and subjective feedback as they flew the scenarios in experiments using progressively higher fidelity simulation, from a medium fidelity general aviation computer simulation [16-18] to the Cirrus SR22 aircraft in flight. Consistent early results across the various experiment platforms, including the high-fidelity HVO Flight Experiment, provided confidence in the results derived from the simulation environment [16-18]. Subsequently, two additional simulation experiments were conducted [19, 20] and determined that non-normal HVO procedures were acceptable to the pilot as well as the procedure support automation, the pilot advisor, developed by NASA researchers [14, 19]. Also, an ATC simulation study was completed and focused on determining controller acceptability of the concept model [12].

6.1 Pilot Validation [16-20]

Results of pilots' flight technical error and their subjective assessments of workload and situation awareness indicate that the SATS HVO concept is viable. The HVO Flight Experiment, flown on NASA's Cirrus SR22, used a subset of the HVO Simulation Experiment scenarios and evaluation pilots in order to validate the simulation experiment results. The evaluation pilots easily transitioned their simulator experience and familiarity with HVO procedures to the flight deck.

Results of the subjective assessments revealed that all twelve low-time instrument-rated pilots preferred SATS HVO when compared to current procedural separation operations. Pilots expressed their frustration with the lengthy hold maneuvers on the Baseline scenarios and their relief at being able to fly the more efficient SATS approaches. Evaluation pilots maintained airspeed and lateral path more accurately when they performed the SATS scenarios than when they performed the Baseline scenarios. They also maintained altitude equally well in both SATS and Baseline scenarios. By observations of lateral path error data, the significant pilot improvement for the SATS scenarios is intriguing because the flight guidance system (HSI and multi-function display with moving map and traffic) was identical for both Baseline and SATS scenarios. While not the focus of study, it can be surmised that the pilots were more "engaged" in the SATS arrival sequence process, anticipating their next maneuver, instead of reacting to ATC clearance, and thus they flew more precisely. The notion that the SATS HVO flight procedure itself produces better flight performance was a surprising observation and merits further study. Evaluation pilots also assessed their workload to be lower in SATS scenarios, and increased situation awareness with respect to traffic and navigation guidance.

Supporting the SATS pilot has been a goal of the research and while minimally qualified (low-time instrument rated) pilots were the evaluation pilots in the HVO Simulation and Flight Experiments, more experienced and qualified pilots should be able to fly SATS HVO as well. The HVO flight tasks were reviewed by evaluation pilots as a logical extension of the instrument rating so should easily merge with FAA training and certification curriculum without adding significant requirements. Evaluation pilots also performed HVO tasks well with the simple NASA Cirrus SR22 research avionics configuration, so improved avionics (including a primary flight display) may simplify tasks further.

6.2 Controller Validation [12]

Integrating HVO into the NAS meant extending procedures and communications into both the terminal and en route air traffic control environments. A joint NASA/FAA simulation was developed and certified professional controllers evaluated the concept. The stated objective was to "demonstrate the viability of SATS HVO airspace transition procedures within the current and future NAS from an air traffic control perspective; specifically, through controller workload and acceptability assessments [12]."

Using the FAA's William J. Hughes Technical Center Target Generation Facility (TGF), controllers from Washington Air Route Traffic Control Center and from Philadelphia Terminal Radar Approach Control (TRACON) evaluated the HVO concept. Three simulation experiments were conducted: 1) the Terminal Sector, 2) the En Route Sector, and 3) Linked En Route Sector (controllers at FAA Technical Center linked live to HVO pilots at NASA Langley).

Controllers were able to hand off aircraft quicker (much faster arrival rate) with the HVO concept compared to today's procedures, and generally had decreased workload. The HVO concept was well received by the controllers who also felt it could be implemented. Areas identified for further research include airspace requirements and design, pilot and controller procedures, controller training, and display of information to the controller and the handling of non-equipped aircraft [12]. Based on the HVO team's consideration of the unresolved issues identified to date, reasonable solutions can or have been identified for all of them [21].

7 Phase Four: Results Validation

The conclusion of the HVO validation process occurred at the 2005 SATS Technology Demonstration held in Danville, Virginia [22]. This fourth phase of the HVO validation research publicly demonstrated the concept as six different aircraft from the six SATSLabs flew the HVO procedures in front of international government and industry stakeholders, media and the public including representatives from US Congress and state legislatures, and FAA and NASA administrators and program leaders. The success of that demonstration is still being echoed in aviation circles and is a tribute to the HVO team's design and research process. Results have been incorporated into the development of the Next Generation Air Transportation System (NGATS) vision and offer a validated method to provide a significant portion of the 3X capacity improvement sought after in the United States' NAS.

8 Future Work

The SATS Program formally ended in 2005, but many HVO research issues still remain. Here are some of them [10]:

- Integration of SATS aircraft into the traffic flow management (TFM) system to avoid creating NAS congestion. This is especially true for airports within TRACON environments.
- Optimize/Tailor the SCA. The size of the SCA may be reduced if the missed approach path exited the SCA, but the pilot-ATC workload may be substantial.
- Optimized instrument approach designs. Research should examine configurations and handling circling approaches.
- Airspace activation. How will the SCA be turned on or off, and who will activate it?
- Runway selection. How will the active runway be established? How the AMM get the information? How will pilots know?
- Controller visibility into the SCA. Procedural and human factors issues.
- Multiple runway operations. Research has not yet been conducted into multiple runways, either parallel or crossing.
- Safety and Hazard Analysis. A safety and hazard analysis of the HVO concept needs to be conducted by the FAA.
- Equipment. What will be the minimum equipment in order to fly and operate within the SCA?
- Training. A training program and requirements for both pilots and controllers needs to be set.

Summary

This document provides an overview of the validation process of the Small Aircraft Transportation System (SATS) Higher Volume Operations (HVO) concept for normal conditions. Results reveal that the concept provides reduced air traffic delays when compared to current operations and was favorably validated by batch study, formal methods analysis, as well as pilot and controller studies. All four validation phases provided feedback to the improvement of SATS HVO and ultimately toward recommending a viable way to improve upon the one-in/one-out procedure in place in the National Airspace System today. HVO study results have been incorporated into the development of the Next Generation Air Transportation System (NGATS) vision [2] and offer a validated concept to provide a significant portion of the 3X capacity improvement sought after in the United States' NAS.

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