Civil Tiltrotor Aircraft Operations

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The goal of the current study is to investigate the benefits and challenges of operating a notional fleet of civil tiltrotor aircraft (10-, 30-, 90-, and 120-passenger vehicles), in the commercial transport role, in the projected Next Generation airspace system. Considerable effort was expended in modeling and performing ACES airspace simulations of this civil tiltrotor (CTR) fleet. An extensive set of airport networks (assuming on- or near-airport property vertiports for CTR VTOL or STOL operations) were also modeled in the airspace simulations. In particular, the networks were mapped to three primary regions: the Northeast Corridor, an Atlanta regional network, and a Las Vegas regional network. Using JPDO demand/capacity projections for 2025 as a baseline, the potential impact of CTR fleet introduction to these regional networks was assessed. The NAS-wide average delay decreased from ~22 minutes for the conventional fixed-wing fleet baseline to 7-8 minutes with the combined introduction of the CTR fleet throughout all three primary regional networks. The study will next consider the operational implications of this notional CTR fleet in supporting major regional and/or National emergencies and disaster relief efforts. The CTR disaster relief analysis is being performed by means of specialized simulation tools. This work re-emphasizes the unique role of rotorcraft in supporting such life-saving missions.

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Acronyms

Airspace Concept Evaluation System (airspace simulation tool)					
Aviation Environmental Design Tool (FAA/Volpe analysis tool)					
Air Traffic Management					
Base of Aircraft DAta (Eurocontrol-developed aircraft performance model)					
Airport code for Boston Logan International					
Concept of Operations					
Conventional Fixed-Wing aircraft					
Conventional Rotorcraft; i.e. helicopters					
Civil Tiltrotor					
Enterprise architecture					
Newark Liberty International					
Federal Aviation Authority					
Feet per Minute, as in CTR climb/descent rates					
Glide Slope, Deg.					
Joint Planning and Development Office					
Airport code for Los Angles International					
Airport code for Miami International					
Nacelle Angle, deg. (NAC=0, CTR airplane-mode; NAC≈90, helicopter-mode)					
National Airspace System					
Next Generation Air Transportation System					
Pilot in the loop					
Runway Independent Operations					
Simultaneous Non-Interfering					
Short takeoff and landing					
Vertical takeoff and landing					

Introduction

CIVIL tiltrotor (CTR) aircraft are an emerging new class of vehicles. NASA research into tiltrotor aircraft spans decades of effort—beginning with the pioneering work with the XV-3, followed by the extremely successful XV-15 program, and currently being sustained through a wide spectrum of aeromechanics research investigations considering the design ramifications of CTRs as large transport aircraft. Recently, these investigations have been expanded to consider both the vehicle fleet and the operational requirements/constraints required of CTR aircraft operating in the projected NextGen airspace environment.

The potential impact of introducing civil tiltrotors into the National Airspace System (NAS) has been the subject of several comprehensive studies dating back to 1987 (Refs. 1-8). CTRs are expected to successfully compete with fixed-wing aircraft provided a supporting infrastructure (ground facilities and air traffic control) is in place. During 2001-2004, NASA sponsored or co-sponsored several studies (Refs. 9-11) of the Runway Independent Aircraft or RIA model of operations whereby existing stub runways could be used by VTOL operating in STOL mode in addition to operating in VTOL mode from vertiports. This operational concept has the potential to increase the capacity of the air transportation system. The increased capacity could then be used to increase throughput or reduce delay significantly throughout the system. Correspondingly, in 2005, the NASA Heavy Lift Rotorcraft Systems Investigation (Ref. 12) examined in depth several rotorcraft configurations for large civil transport, designed to meet technology goals of the NASA Vehicle Systems Program. The investigation identified the Large Civil Tiltrotor (LCTR) as the configuration with the best potential to meet the technology goals (Fig. 1). Additionally, since the studies of the late-1980's and early 1990's, recent events demonstrating the critical role of rotorcraft in disaster (man-made and natural) relief provide another compelling need for civil transport rotorcraft to be fully incorporated into the next generation airspace system. In short, the role of advanced, high-speed rotorcraft designed for civil transportation should be re-visited to account for advances in rotorcraft technology, advances in airspace modeling, and the more prominent role of rotorcraft in public safety. Advanced civil tiltrotors, however, must be considered within the context of the Next Generation Air Transportation System, aka "NextGen."



Fig. 1 - NASA Large Civil Tiltrotor (LCTR2) reference design

The Joint Planning and Development Office (JPDO) was instituted to address the challenges facing air transportation in the United States by engaging multiple agencies that would collaborate to plan, develop, and implement the Next Generation Air Transportation System. The JPDO has formulated initial versions of the NextGen Concept of Operation (CONOPS) and Enterprise Architecture (EA) - see Refs. 13-15, respectively – and continues to refine the CONOPS and EA as progress is made toward implementation of NextGen. These documents provide details regarding "what" NextGen is, as envisioned for operation in 2025. The CONOPS provides a broad vision for the air traffic system and the vehicles that operate within it. To realize that vision, the CONOPS must be informed with tangible details of the "how" to accomplish NextGen - this "how" is the focus of NASA research in support of NextGen. NASA's role is discussed in a recent white paper (Ref. 16). By way of example, one of the anticipated key benefits of the NextGen airspace is the ability to fly more direct routes to city-pair destinations; see Fig. 2. All three of the NASA Aeronautics Research Mission Directorate (ARMD) research programs (Fundamental Aeronautics, Aviation Safety, and Airspace Systems) contribute directly and substantively to NextGen. Recently completed NASA Airspace Systems Program sponsored studies, Refs. 17-18, have sought to understand how advanced vehicles will operate within NextGen as well as examine the tradeoffs involved for vehicles and the air traffic management (ATM) system, including safety considerations, system performance, environmental constraints, and other relevant issues.



ACES Fix-Based Conventional Routings

Mixed-Equipage Conventional Routings



One of the anticipated ways of achieving more efficient and more direct flow through the NAS is the adoption of four-dimensional trajectories, through the use of "flow corridors" and other methods (see Fig. 3). NextGen satellite-based guidance, navigation, and communication will be particularly crucial for enabling simultaneous non-interfering (SNI) flight and runway-independent operations (RIO) in terminal areas. Many past and current airspace simulations were conducted assuming 100% NextGen-compatible equipage for CTR aircraft; a mixed-equipage level (70%) was assumed for the conventional fixed-wing (CFW) aircraft fleet, circa 2025, though, for this study. The mixed-equipage level for the CFW fleet was deemed by the study team members as being a more realistic scenario than assuming full-equipage for the CFW aircraft.



Fig. 3 – NextGen "Flow Corridors" and the challenges of adopting RIO and SNI terminal area "Four-Dimensional" flight trajectories

This paper summarizes some of the ongoing work sponsored by the NASA Fundamental Aeronautics Program's Subsonic Rotary Wing (SRW) project. This work is complementary to Refs. 17-18 and examines the benefits and challenges associated with deploying a fleet of civil tiltrotors (CTRs) into the projected NextGen environment. The study explores the system trades among operational procedures, CTR capabilities, and overall NextGen performance. The team performing this study includes: SAIC, the contractor programmatic lead, as well as responsible for vehicle/airspace concept of operations definition; Bell Helicopter Textron, vehicle conceptual design, pilot-in-the-loop simulation, and rotorcraft/disaster-relief modeling; Sensis, regional and NAS airspace systems modeling and simulation; Optimal Synthesis, terminal area procedures and modeling. The study will endeavor to determine: (1) how the procedures and concepts of operations for CTRs impact the performance of the overall airspace system; (2) approaches to ensuring the safety of the CTRs and the system; (3) possible modifications/enhancements to the NextGen CONOPS in order to accommodate CTRs; (4) environmental effects of CTR fleet introduction; and (5) the possible implications for the development of future rotorcraft and the NextGen airspace.

The present study has many elements. First, vehicle conceptual design and sizing analysis work has been conducted to identify and categorize the potential attributes of a fleet of civil tiltrotors (CTRs) as they affect operation in NextGen in 2025 and beyond. The notional fleet being studied consists of four sizes of CTR aircraft: 10, 30, 90, and 120 passengers. This tiltrotor conceptual design and vehicle sizing work was performed by Bell. Bell conceptual design work complements other recent NASA and NASA-sponsored large civil tiltrotor reference designs (Refs. 19-20). In parallel with the vehicle fleet conceptual design definition, procedures are being developed for how the fleet of CTRs will operate in the NextGen airspace. Vertical takeoff and landing (VTOL), in addition to short takeoff and landing (STOL), approaches will be

considered (Fig. 4). CTR vertiports located at high-density airports and possibly city centers will be accounted for in the airspace terminal area modeling.



Fig. 4 - Challenges of integrating VTOL and STOL CTR aircraft operations at high-density airports

To support the CTR fleet simulations, metrics were identified to assess the impact of CTR operation on NextGen performance. Additionally, a noteworthy technical challenge for the overall effort was to identify appropriate analytical tools to support the study and modify or develop models, as necessary, to enable analysis of the effects of CTR runway-independent operations (RIO) and simultaneous non-interfering (SNI) terminal area procedures. In addition to the CTR airspace simulation effort, a preliminary assessment of the key safety considerations associated with operation of the CTR fleet is also being developed, including potential hazards and mitigation strategies, the effect of off-nominal conditions, and potential certification issues. Finally, and particularly crucial for rotorcraft which are well known to be critical public-service aviation assets, the impact of a CTR fleet on disaster relief operations will be examined. A scenario will be developed for a major U.S. urban area where runways, rail systems, and surface-road networks are disrupted. The operation of the CTR fleet in this scenario will be developed and discussed. This discussion will include the role of CTRs in mass domestic relief efforts (evacuation, ferrying supplies, policing, etc.), CTR interaction with other aerial vehicles and ground/sea-based platforms/assets, and details of operations such as staging, command and control, and crew requirements. Trade studies examining parameters such as tons-of-supplies-delivered-per-unit-time, or evacuations-perunit-time will be performed looking at relative mixes of CTRs versus other (aviation) transportation assets.

Conceptual Design of a CTR Fleet

A fleet of CTR aircraft was designed by Bell Helicopter Textron. Conceptual designs for four aircraft sizes were devised: 10-, 30-, 90-, and 120-PAX vehicles.[§] The CTR conceptual designs were developed using the Bell PRESTO code (Ref. 35). Previous civil tiltrotor studies typically focused on only one vehicle conceptual design as being emblematic of the whole vehicle class. Having a spectrum of vehicle sizes included in the airspace study provides many advantages. First, CTR aircraft will likely be introduced

[§] Initially the 90-PAX vehicle characteristics were simply scaled from the 30- and 120-PAX conceptual designs. A later, separate contract task was performed to generate a complete 90-PAX conceptual design.

into operation in order of vehicle size. Smaller vehicles, e.g. Ref. 31, will undoubtedly be introduced at an earlier date as compared to larger vehicles. Second, despite several studies conducted in the past, the optimal size of an economically competitive CTR is unclear; studying a fleet of vehicles of varying sizes should help provide insight into this issue. Third, different market segments will likely be served by this spectrum of vehicle sizes and passenger capacities. For example, small vehicles will tend to provide airtaxi type services. Mid-size vehicles would likely be used mostly for limited-scheduled-service flights in and out of suburban vertiports and/or under-utilized regional airports, with the occasional connector flights into the major airports. Finally, the larger vehicles would likely be competing against fixed-wing turboprop and regional jet aircraft for regularly scheduled short-haul commuter flights in and out of highdensity airports. Figure 5a-b provides design drawings of the 120-PAX CTR design. The 10- and 30-PAX vehicle designs draw upon significant design heritage from near-production and production aircraft, particularly with regards to the dynamic drive train systems; however, among other technologies, advanced composite technology is incorporated into the aircraft airframes. The 120-PAX and the 90-PAX vehicle CTR aircraft, however, are clean-sheet designs reflecting a spectrum of technology advances that are anticipated prior to aircraft development.



Fig. 5 – 120-PAX CTR conceptual design layout: (a) airplane-mode and (b) helicopter-mode

Figure 6 is the proposed cabin layout for the 120-PAX CTR. As the aircraft is intended to be a civil passenger transport, requirements in terms of emergency exits, galley, lavatories and number of attendants are set by FAA rules. These FAA rules are reflected in the cabin layout shown in Fig. 6.



Fig. 6 – 120-PAX CTR cabin design

Table 1 summarizes some of the key design requirements used for the notional CTR fleet conceptual design effort. These design requirements were partly informed by previous NASA reference design work, as well as reflecting the study team's subject matter expertise. Additionally, the speed/range requirements for the larger vehicles reflected the team's desire to push the technology limits of the aircraft. For example, previous CTR studies have emphasized the short-haul market potential of the aircraft. In this study, the conceptual design requirements were set to examine longer-range markets, especially since large civil tiltrotor aircraft may also support public service missions such as disaster relief and emergency response efforts.

Table 1 – CTR fleet initial design requirements

Number of Passengers	10	30	90	120
Takeoff Condition	5k/Hot	>	>	>
Takeoff Procedure (1)	VTOL (2)	VTOL (2)	VTOL	VTOL
Payload, Ibs	2200	6600	19800	26400
Design Range, nm	800 ⁽²⁾	1000 ⁽²⁾	1000	1500
Cruise Altitude, 1000's ft	25	25	30 ⁽²⁾	30 ⁽²⁾
Cruise Speed, ktas	Fallout	Fallout	300 (2,3)	350 ⁽²⁾

(1) VTOL is assumed to be a Transport Category procedure (same as Cat A) (2) Target (3) At 90% MCP

Note that in order to meet one-engine-inoperative (OEI) design requirements, the larger CTR aircraft have four engines (two per rotor) instead of the two engines seen in current designs. Another interesting aspect of the larger CTR is the large number of blades per rotor. Current tiltrotor aircraft designs have three-bladed rotors; the 30-PAX CTR has four-bladed rotors and the 90- and 120-PAX designs have six-bladed rotors. Finally, for improved acoustic characteristics and improved cruise efficiency, the 30-, 90-, and 120-PAX aircraft will operate at significantly lower rotor tip speeds than current tiltrotor aircraft

designs. Additional details for the CTR conceptual designs can be found in Ref. 37-38.

The aircraft mission performance characteristics, as derived from the Bell PRESTO code, were subjected to regression analysis. These regression analysis results, in turn, were translated into BADA models (Ref. 21). As the BADA models are nominally crafted for fixed-wing aircraft only, the BADA coefficients were manipulated to emulate the characteristics of CTR aircraft. The intent was to use the BADA models as input data to the ACES and AvTerminal airspace simulation tools. However, not all BADA model parameters were supported by the two airspace simulation codes ACES and AvTerminal. This ultimately drove SAIC to develop Matlab-based software tools that took full advantage of both the regression analysis results from PRESTO and the BADA model framework. One of the tools, the "Performance Deck," served two purposes: refine the flight profiles for a particular combination of CTR vehicle and city-pairs; generate mission performance profiles. These mission performance profiles, in turn, were used to validate the ACES and AvTerminal airspace simulation results. The other Matlab-based tool was a "plug-in" module to be directly interfaced to ACES and AvTerminal. The development of this plugin module was critical to estimating accurate fuel-burn rates for the CTR aircraft using the two airspace simulation tools, which were developed solely for fixed-wing aircraft. Extensive effort was expended to force these fixed-wing models and airspace simulation tools to emulate CTR flight operations.

Figure 7 illustrates the general process by which the BADA-modeling format information and the Matlab-based Performance Deck are verified against the Bell conceptual design mission performance characteristics. Further verification is achieved by using the 10, 30 and 120 passenger CTR BADA models to generate a "scaled" 90 passenger vehicle which, in turn, can be compared to a design independently generated by Bell. Such validation and verification was continued with correlation of ACES and AvTerminal performance output (integrated with the SAIC Matlab-based post-processor plug-in module) against Bell mission performance numbers.



Fig. 7 – Process for developing and validating BADA input for ACES airspace simulations using Bell PRESTO sizing tool results and Bell Pilot-in-the-Loop simulation data

Table 2 presents representative configurations for validation and verification. In Fig. 8, the Bell mission fuel-burn estimates are compared to the ACES-integrated CTR fuel-burn post-processor module. Good agreement was found for most of the verification test cases studied. Similar verification test cases were performed for the 10, 30 and 120 passenger CTR aircraft. For additional details regarding the validation and verification testing on ACES and AvTerminal incorporating the CTR BADA-modeling and post-processor plug-in modules, see Ref. 38.

Test Case	Description				
41	Initial Climb Configuration @ level flight (NAC 60 deg)				
49	Approach Configuration @ -6 deg GS (NAC 75 deg)				
45A	STOL Landing Configuration @ level Flight (NAC 90 deg)				
51A	STOL Landing Configuration @ -6 deg GS (NAC 90 deg)				
45B	VTOL Landing Configuration @ level Flight (NAC 90 deg)				
51B	VTOL Landing Configuration @ -6 deg GS (NAC 90 deg)				
38A	STOL Takeoff Configuration @ level flight (NAC 60 deg)				
54A	STOL Takeoff Configuration @ +500 FPM Climb (NAC 60 deg)				
38B	VTOL Takeoff Configuration @ level flight (NAC 85 deg)				
54B	VTOL Takeoff Configuration @ +500 FPM Climb (NAC 85 deg)				

Table 2 – Static trim verification check-case configurations defined.

Static Fuel Burn Rate Comparison All Points at BADA Reference Weight (125,000 lbs) Various Conversion Modes 120-pax CTR



Fig. 8 – Fuel-burn comparison between ACES with the Fuel-Burn Post-Processor (FBPP) and Bell PRESTO analysis for 120 passenger CTR; conversion-mode static trim comparison data

CTR Airspace, Including Terminal Area, CONOPS

In order to support the overall airspace simulation effort, pilot-in-the-loop (PITL) simulations were conducted in Bell Helicopter Textron facilities. CTR operations in and out of the Miami airport were flown in the simulator by an experienced tiltrotor aircraft test pilot. Refer to Fig. 9 for a cabin view of the PITL simulation. These fixed-base simulations examined some of the key terminal-area operational characteristics of CTR aircraft. Several simulation test runs were conducted of aircraft having the approximate characteristics of the 10- and 30-PAX CTR designs. Both STOL and VTOL modes of operation during takeoff and landing were investigated in the PITL simulation. Further, both straight-in and spiral approaches were also studied. In all test runs, a substantial body of test data was acquired so as to validate the Bell PRESTO (Ref. 35) conceptual-design-tool-derived mission performance estimates as

well as the SAIC-developed "Performance Deck" Matlab-based tool. After the simulations were completed, test pilot and engineering subject matter expertise were employed to qualitatively generalize the simulation results and overall expert operational experience to the larger CTR aircraft.



Fig. 9 - Cabin view during the Pilot-in-the-Loop simulation

The test results from the PITL simulations had a major influence in defining the generic flight profiles incorporated into the CTR airspace simulations being conducted by the study team.

The successful introduction of civil tiltrotor aircraft for commercial aviation transport will be dependent on the concurrent infrastructure investment in on- or near-airport-property vertiports (Refs. 22-24) as well as complementary, but secondary, network of city-center and suburban vertiports. For commercial aviation transport, the development of on- or near-airport-property vertiports will be essential. Consequently, identifying credible on-airport-property vertiport notional sites at a few key airports was an important consideration in the preliminary effort leading up to the NASA-sponsored-developed ACES (Ref. 33) and the Sensis-developed AvTerminal (Ref. 34) airspace simulations.

Selecting airport real estate at a well-established fixed-wing airport to host a suitable vertiport can be a challenge. In order to establish a ground footprint for such a landing zone suitable for the CTR variants in this study, FAA AC 150/5390-3 entitled "Vertiport Design," Ref. 22, was consulted for guidance. This AC recommends geometry for the following vertiport landing site components: Touchdown and Lift-Off Area (TLOF), i.e. the prepared (hard/paved) landing surface; Final Approach and Takeoff Area (FATO), i.e. area where final approach transitions to hover for landing and the area where the takeoff maneuver is commenced. These areas must be clear of obstacles to provide a VTOL landing pad. AC 150/5390-3 specifies the landing pad dimensions (as shown in Fig. 10) for a tiltrotor aircraft with an effective rotor span (RS) of 100 ft. Scaling these dimensions based on actual CTR RS was performed, as recommended in

the AC, to develop a suitable footprint requirement based on the CTR10, CTR30, CTR90, and CTR120 variants in this study. The resulting VTOL landing-site dimensions were determined assuming the more stringent IFR conditions for TLOF sizing: CTR120, assume RS 191ft, therefore, FATO = 478'x478' and TLOF = 287'x287'; CTR90, assume RS 142ft, therefore, FATO = 355'x355' and TLOF = 213'x213'; CTR30, assume RS 84.58ft, therefore, FATO = 212'x212' and TLOF = 127'x127'; CTR10, assume RS 60ft, therefore, FATO = 150'x150' and TLOF = 90'x90'.



Fig. 10 - VTOL landing pad dimensions with a 100 ft effective rotor span (RS)

With this general vertiport sizing information, Ref. 37 performed a limited qualitative assessment of vertiport siting issues and identified a number of potential sites at LAX, MIA, and EWR. Each of the identified potential vertiport sites has its relative strengths and weaknesses. Using subject matter expertise within the study team, these sites were notionally narrowed down to a single site for each airport. LAX was the original anticipated site location for the pilot-in-the-loop simulation at Bell Helicopter; the PITL simulation was ultimately conducted for MIA. To support the PITL simulations, notional vertiport sites were defined for both airports. In turn, vertiport sites were identified for EWR because of Sensis' past terminal-area modeling and simulation experience using AvTerminal for this particular airport (Ref. 34); this past experience was a key factor in using EWR as a benchmark for establishing terminal-area RIO/SNI procedures for CTR's. Modeling information and insights from EWR were then used to arrive at relevant modeling input for other network airports.

The results suggested that even at high-density airports, there exist site locations that could potentially be converted or transformed into vertiport facilities. Since these on-airport-property vertiports would increase airport capacity through better utilization of airport real estate, a business case could be developed that would encourage airport operating authorities to invest in vertiport infrastructure. However, this study was only a very preliminary assessment of on-airport-property vertiport siting, many other issues need to be considered, such as influence of CTR downwash on ground facilities, ground assets, and parked or taxiing light aircraft (Ref. 26) (see Fig. 11). Additionally, minimizing the amount of time from aircraft pullback from the jetway to the time of actual takeoff is crucial to the success of a CTR as a commercial passenger transport. Since the CTR has slower cruise speeds, compared to most turboprop and regional jet aircraft, fast turnarounds on the ground are very important (Ref. 27).



Fig. 11 - On- or near-airport-property vertiports (Vertiport Image Courtesy of Sukra-Helitek)

The ability to perform both STOL and VTOL operations gives CTR aircraft considerable flexibility. For underutilized airports, or during non-peak hours, CTR aircraft would likely operate in STOL mode on longer runways. During peak hours at high-density airports, CTR aircraft could either perform STOL operations on short, stub runways and/or converted taxiways or perform VTOL operations from dedicated vertiports. Each mode of operation has its own relative advantages and disadvantages. For STOL operations, takeoff and landing consumes less power and therefore less fuel than VTOL operations; however, this comparative fuel efficiency is operationally partly offset by the fuel-burn during required taxi-in and taxi-out to the stub runway/taxiway as well as a comparative increase in total gate-to-gate time due to taxiing. Finally, wind conditions, temperature/altitude conditions, and passenger/cargo loads can all be important considerations in whether a given CTR aircraft takes off or lands in STOL versus VTOL mode. For example, Denver on a hot day may dictate STOL mode operations only for the smaller 10 and 30 passenger CTR aircraft.

For almost all of the ACES airspace simulation work performed for the CTR fleet, VTOL mode was employed for takeoff and landing and only a limited amount of STOL mode assessments were performed. Accordingly, defining vertiport characteristics, particularly in terms of capacity was important (see Fig. 12a). Given an assumed vertiport capacity and estimates of the nominal CTR demand, an estimate of the required number of vertiports for certain airports was projected. Only one vertiport was required to support CTR traffic at the majority of the airports considered. However, for a select few high-density airports, more than one vertiport was required to support the projected CTR arrivals/departures; this is summarized in Fig. 12b. Atlanta clearly leads with a projected six vertiports required to support CTR arrivals/departures. The CTR airspace simulation NAS-wide delay estimates that follow in the next section of the paper are highly dependent on not only the size of the CTR fleet but the number of on- or near-airport-property vertiports supporting them.



Fig. 12 - Assumed (a) vertiport capacity and (b) number of vertiports at key airports

Finally, as noted earlier, establishing the size of CTR fleet, prior to performing airspace simulation work was crucial. Sizing the CTR fleet was extremely challenging for a conceptual vehicle that relies on advanced technologies that are currently at modest TRL levels and on untried business models. To project aircraft demand, and validate against an assumed development and production schedule, is not feasible given the circumstances. The alternative approach, taken in this study, is to effect a short-haul aircraft substitution strategy whereby existing conventional fixed-wing aircraft of a certain size class, i.e. number of passenger seats, is replaced with an approximately equivalent-sized CTR. Specifically, replacement of conventional fixed-wing aircraft schedule capacity was done on a seat-for-seat basis. The short-haul CFW demand is based upon FAA projections for circa 2025. The CTR short-haul substitution strategy implicitly assumes that the relative economic competitiveness between CTR aircraft and the replaced short-haul CFW is not an impediment to the substitution. Table 3 summarizes the number and type of CTR aircraft, estimated by means of the seat replacement/substitution strategy just noted, in three regional networks.

Region	CTR 30	CTR 90	CTR 120	CTR Total
ATL500	3	21	27	51
LAS500			14	14
NEC500	38	71	54	163
Total	41	92	95	228

Table 3 – CTR Fleet Size

CTR Airspace Simulation Results

One of the key outcomes of the BADA modeling exercise, besides providing necessary input data for the ACES simulation tool, was the development by SAIC of two complementary Matlab-based software tools: a standalone "Performance Deck" to examine CTR mission performance and a fuel-burn post-processor (FBPP) "plug-in" module to directly interface with ACES.

As noted before, the key objective of the current study is to study the potential of civil tiltrotor aircraft to moderate airport/terminal-area airspace congestion, in conjunction with planned NextGen air traffic management advances. The original focus of the ACES airspace simulations for the CTR fleet was to be focused on an airport network in the "Northeast Corridor." Nine airports are included in this original network: BOS, BWI, DCA, EWR, IAD, JFK, LGA, PHL, and PIT. After initial ACES simulations, this small network was deemed an inadequate foundation to make NAS-wide average delay estimates for the notional CTR fleet. Fortunately, software tools developed during the CTR study resulted in highly-automated processes for modeling the CTR fleet and associated vertiports. This allowed a substantial increase in the number and size of regional networks incorporated into the airspace simulations. These much larger networks ensured that the airspace simulation results could be reasonably "scaled" to yield NAS-wide estimates of aircraft mean delay and other critical metrics. Figure 13 illustrates the three regional networks incorporated into the final ACES airspace simulations: the ATL, LAS, and Northeast Corridor networks. These regional networks included all city-pairs within 500 statute miles of each other.



Fig. 13-30, 90, and 120 passenger CTR aircraft mixed-fleet regional networks

Figure 14a-b shows the projected delays, circa 2025, for a key subset of airports. Figure 14a presents the estimated delays for a baseline CFW fleet of aircraft and Fig. 14b presents the delay estimates after the introduction of a mixed fleet of 30, 90, and 120 passenger CTR aircraft into the Fig. 13 three regional-Projected delays in ATL, LAS, and a number of the Northeast Corridor airports are networks. substantially reduced by the CTR fleet introduction. As an aside, SAN (San Diego) and MDW (Midway) experience modest-to-little delay reduction with the CTR fleet introduction. Follow-on airspace simulation work would be required to fine tune the CTR fleet and networks to potentially reduce delays at these It is anticipated that NAS-wide average delays will also see significant reductions as a airports. consequence of reducing delays at targeted airports.



(a)

Fig. 14 – Delays for a mixed CTR fleet of 30, 90, and 120 passenger aircraft

Figure 15 summarizes the significant NAS-wide delay reduction potential of operating a notional CTR fleet in the three primary regional networks shown in Fig. 13. The average NAS-wide delay, in minutes, is presented as a function of the introduction of CTR aircraft types into the regional networks. Note that each bar in Fig. 15 includes not only the influence on the NAS delay for the particular vehicle type and network noted at the base of the bar but also includes the cumulative effect of the bars to the left of a given bar. The baseline delay, for a conventional fixed-wing fleet with mixed-equipage (70% of CFW fleet equipped with NextGen-compatible avionics), is estimated at approximately 21.5 minutes (refer to the leftmost bar in the Fig. 15 bar-chart). The introduction of 120-passenger CTRs (CTR-120) into the Atlanta regional network had the single largest effect, reducing the NAS-wide average delay down to approximately 12.75 minutes. The next largest impact was the introduction of CTR-120 aircraft into the Las Vegas network with the cumulative NAS-wide delay reduced to approximately 9.5 minutes (the average delay estimate reflects the cumulative effect of CTR-120 aircraft operating in parallel in both the Atlanta and Las Vegas networks). Each successive bar to the right represents the cumulative effect of either a new vehicle type and/or network; however, the incremental effect, as one moves to the right on the bar-chart, becomes minimal. The minimum NAS-wide average delay estimated was a little over 7 minutes; further, the introduction of 30 passenger CTR aircraft, on top of the introduction already of CTR-120 and CTR-90 aircraft, had a marginal effect on NAS-wide average delays. Whether there is an optimal trade-off between CTR-90 and CTR-120 aircraft for initial introduction into the critical Atlanta and Las Vegas networks is unclear; such a trade-off assessment will have to await some future study.



Fig. 15 - Average delay reduction (NAS-wide) from CTR substitution

Figure 15 results suggest that the targeted introduction of CTR aircraft and vertiports may have a substantial leveraging effect on reducing NAS-wide average delays. This is perhaps particularly true for the targeted introduction of large CTR aircraft into an Atlanta-based network. For more details regarding the CTR fleet airspace simulations and their underlying analysis approach, see Ref. 38.

Preliminary CTR Noise, Fuel-Burn, and Carbon-Emission Estimates

After completing the ACES airspace simulation work, an initial assessment of CTR fleet noise and emissions was attempted. The CTR noise and emissions analysis was originally going to be performed using a beta-release version of a next-generation analysis tool being developed by the FAA and the Volpe National Transportation Systems Center called the "Aviation Environmental Design Tool" (AEDT) (Refs. 28-29). Attempting to perform noise and emissions work with the then-beta-release AEDT was particularly challenging for a number of reasons and ultimately abandoned for this study. Instead, the emission work for this study was restricted to making carbon estimates, based on fuel-burn estimates from the ACES simulations (using the fuel-burn post-processor tool developed specifically for the CTR fleet). The noise work was restricted to a very preliminary investigation at a single airport, EWR, the Newark Liberty International Airport, using the well-known noise prediction tool INM. Newark was already wellmodeled, through past studies, with respect to terminal area flight-profiles/trajectories. The present work is a limited, initial attempt to better understand the noise and emission consequences of the introduction of civil tiltrotor aircraft into the NAS. Considerably more work in the civil tiltrotor aircraft noise and emission prediction area needs to be performed in future studies, particularly with an emphasis on the impact of a fleet of aircraft conducting operations out of major airports, some with environmental constraints.

Considering first fuel-burn and the vehicle's carbon emissions, Fig. 16 presents the fuel-burn estimates of a notional fleet of civil tiltrotors as a function of Great Circle distance in nautical miles. The CTR fuelburn estimates are compared to current generation conventional fixed-wing aircraft as estimated from CFW ACES simulation results. The CTR results are also compared to a notional future fleet of conventional fixed-wing aircraft, circa 2025, assuming such a fleet is 25% more efficient fuel-burn-wise as compared to the current fleet. The projected 90 and 120 passenger CTR aircraft fuel burn estimates are roughly comparable to a current generation conventional fixed-wing fleet. However, the CTR fuel burn estimates, when compared to a future fleet of conventional fixed-wing aircraft, fail to close the gap as far as fuel efficiency is concerned. This, therefore, is a technology challenge for CTR aircraft.



Fig. 16 – Preliminary investigation of CTR fleet fuel-burn; CTR vs. conventional block fuel per seat vs. distance

As noted above, the bulk of the INM noise prediction work focused on the Newark Liberty International airport. Figure 17 depicts representative anticipated flight trajectories to/from the Newark and Boston citypairs. Such airspace simulation flight trajectories summarizing all CTR flights into and out of EWR are essential for providing details on the overall additive noise footprint.



Fig. 17 – Illustrative notional CTR flights between Boston and Newark: (a) EWR to BOS and (b) BOS to EWR (Background Images Courtesy of Google-Earth)

Figure 18a-b presents the preliminary noise investigation of CTR fleet operations into and out of Newark Liberty International Airport. Sound Exposure Level (A-weighted) contours for all projected aircraft operations to/from EWR are shown, including an assumed set of 45 in- and 45-outbound CTR flights. The CTR operations were conducted by a mixed-fleet of 30, 90, and 120 passenger vehicles, according to the same seat replacement strategy as discussed earlier. The SEL noise contours are superimposed in Fig. 18b over a population map. No attempt was made in these preliminary results to tailor/optimize the CTR flight-path trajectories to reduce overall noise levels over the neighboring population. Such investigations will have to be conducted in the future.



Fig. 18 – Preliminary noise analysis for the CTR fleet; SEL noise contours of 45 in-bound and 45 outbound flights at EWR using INM; mixed CTR30, CTR90, and CTR120 fleet (Background Image Courtesy of Google-Earth)

An alternative noise metric, Day-Night Average Sound Level (DNL), was estimated using INM for CTR fleet operations to/from EWR; see Fig. 19a-b. For this particular case, the EWR departure and arrival

operations were replace by an all CTR fleet at the same number of the conventional fixed-wing fleet investigated in Ref. 17. The DNL results show the CTR fleet's noise level is similar to the conventional fleet as projected in that particular study, which suggests the CTR fleet's operational noise at the airport is compatible with the conventional fleet.



Fig. 19 – Preliminary noise analysis for the CTR fleet; DNL noise contours of 1491 in-/out-bound flights at EWR using INM (Background Image Courtesy of Google-Earth)

Future Work

The current study will conclude with specialized simulation analyses examining the technological and operational factors governing disaster relief efforts given employment of a hypothetical CRAF-like ("Civil Reserve Air Fleet," see Ref. 36) CTR fleet to aid in large-scale public service missions. Specifically, a Hurricane-Katrina-magnitude disaster scenario will be studied. The utility of rotorcraft for public service missions – especially as related to emergency response and disaster relief operations – is well-known. For example, Fig. 20 illustrates a CTR shipboard-compatibility demonstration conducted in the past for the US Coast Guard. If a CTR fleet is ever successfully introduced, the justifications will be on the basis of the aircraft's economic competitiveness, beneficial impact on NAS and airport operations in relieving congestion and increasing capacity, and recognition of the CTR's inherent capability to meet major national public service challenges. The planned disaster relief scenario simulations will hopefully improve understanding of that public service potential.



Fig. 20 - Potential for CTR for public service missions (Image Courtesy of the U.S. Coast Guard)

Concluding Remarks

It has long been anticipated that civil tiltrotor aircraft could potentially be major contributors to commercial aviation transport. In particular, FAA projections of future air travel demand suggest that unless several crucial steps are taken in the near- and mid-term, airport/airspace congestion will grow to unacceptable levels. One of the key objectives of the FAA NextGen project is to tackle this growing congestion problem using satellite-based systems to aid and assist in the automation of air traffic management. The inherent runway-independent and simultaneous-non-interfering operations of tiltrotor aircraft, in a vehicle-centric manner, could have a substantial positive influence on moderating this anticipated increase in congestion. This assumption is supported by the ACES airspace simulations performed in this study which shows that the NAS-wide average delay was reduced from ~22 minutes for the conventional fixed-wing fleet baseline to 7 to 8 minutes with the combined introduction of the CTR fleet and vertiports into three primary regional networks.

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