Baseline Assumptions and Future Research Areas for Urban Air Mobility Vehicles

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NASA is developing Urban Air Mobility (UAM) concepts to (1) create first-generation reference vehicles that can be used for technology, system, and market studies, and (2) hypothesize second-generation UAM aircraft to determine high-payoff technology targets and future research areas that reach far beyond initial UAM vehicle capabilities. This report discusses the vehicle-level technology assumptions for NASA's UAM reference vehicles, and highlights future research areas for second-generation UAM aircraft that includes deflected slipstream concepts, low-noise rotors for edgewise flight, stacked rotors/propellers, ducted propellers, solid oxide fuel cells with liquefied natural gas, and improved turboshaft and reciprocating engine technology. The report also highlights a transportation network-scale model that is being developed to understand the impact of these and other technologies on future UAM solutions.

I. Introduction

Since NASA first introduced a viable path to Urban Air Mobility in 2003 [1], the focus of NASA's research in this field has been to showcase potential technologies, concepts, and research areas that could realize this vision. Urban Air Mobility or UAM is an emerging market that aims to introduce air passenger and cargo transportation within an urban or metropolitan area through the development of vertical or short takeoff and landing (V/STOL) vehicles. These vehicles will realize a convergence of electric propulsion and autonomous technologies in aviation to radically transform how we commute and travel within an urban core. With the added insurgence of peer-to-peer ridesharing automobile trips, this market could help bring true door-to-door, on-demand aviation into our daily lives.

The Vertical Flight Society reported in July of 2018 that over 100 Urban Air Mobility concepts have been created [2], indicating that this vision is on the cusp of being fully realized. With heightened involvement from industry in the design of first-generation or N+1 UAM vehicles, we propose that NASA must:

1) Develop N+1 reference vehicles that can be used to understand the impact of a researcher's work on the Urban Air Mobility market and
2) Explore a second-generation or N+2 UAM aircraft (similar to our current role in commercial transports) that reaches far beyond the initial capabilities to determine high payoff technology targets and research areas

The purpose of this report is to document the technology assumptions that were used for previous reference vehicles, which will provide a reference baseline for the potential of future technology targets and research areas.

II. Background

The aim of NASA's Revolutionary Vertical Lift Technology (RVLT) project is "to capitalize and improve unique vertical capabilities to greatly benefit the Nation's growing civil flight requirements [3]." In recent years, arguably the largest civil flight requirement for vertical flight has come from UAM. Therefore in January of 2018, Johnson, Silva, and Solis developed three initial reference vehicles in an attempt to "span many elements of [the UAM] design space" (see Fig. 1) [4]. In May, Patterson, Antcliff, and Kohlman published an initial exploration of mission requirements for UAM, which specified design ranges and number of passengers for some potential UAM missions [5]. Using these mission requirements as a guide, Silva, et. al. modified the original concepts and added an additional concept. Specifically, a

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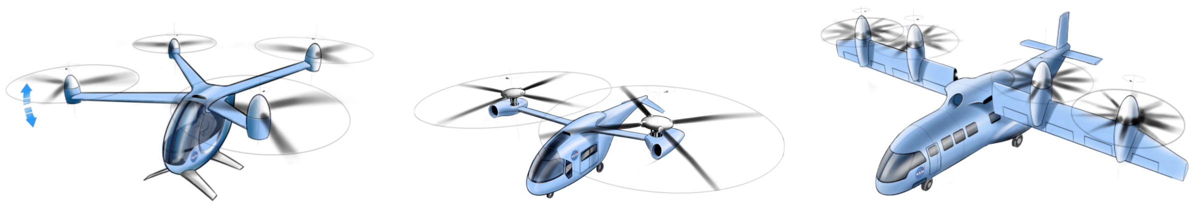


(a) Quadrotor (b) Side-by-Side Helicopter (c) Tiltwing

Fig. 1 The initial UAM reference vehicles.

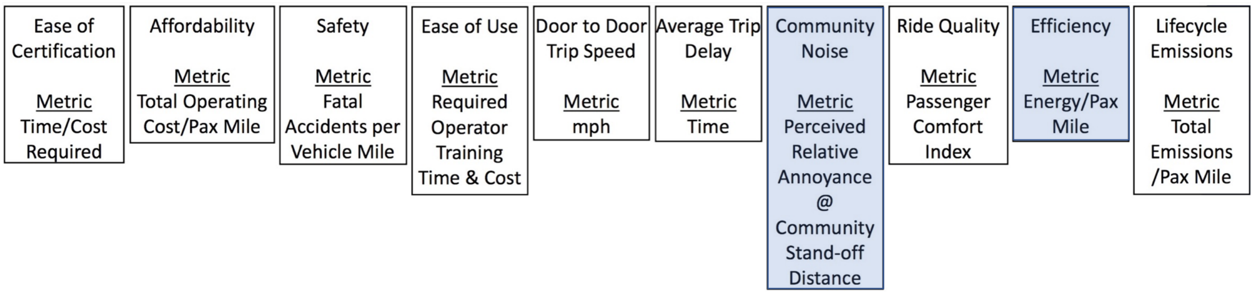


Fig. 2 Community noise and efficiency are the two ODM Workshop barriers that are heavily vehicle-centric

small quadrotor aircraft was scaled up to meet these specific requirements, and a new type of aircraft, a lift+cruise concept, was added to the types of aircraft considered, because it had features which explore some particular technology trades relevant to aircraft being proposed by industry [6]. In this report, the assumptions used in the analysis of the concepts developed in these three studies will be documented. This will ensure consistent technology assumptions for the evaluation of specific technologies on a relevant platform and for baseline vehicles of future N+2 UAM vehicles. As a note, the reference vehicles described in these reports have not been evaluated for noise characteristics, and have only applied some general rules of thumb, primarily the reduction of blade tip speed at a small cost in increased weight for the overall designs.

The two vehicle-specific focus areas for future technology targets and research areas will be efficiency and noise. In 2015 and 2016, NASA held five workshops that brought together more than 120 industry, academia, and government entities to discuss the future of On-Demand Mobility (ODM), which encompasses UAM. One of the main products of these discussions was a consolidated list of key feasibility barriers, research objectives, and potential technologies needed to overcome these barriers. Two of the ten feasibility barriers shown in Fig. 2, noise and efficiency, are highly vehicle-centric and rely on quantifiable technological advances [7]. An additional, quiet-VSTOL-focused "Blue Sky" workshop was held in August 2015, primarily for the purpose of exploring low-noise vehicle concepts for further NASA consideration. Based on the recent development of a UAM transportation system-level model by Kohlman and Patterson [8], a direct relationship between future potential technologies and operating cost of a future UAM transportation system can be achieved. Therefore, a clear connection between the technology targets and how they will be analyzed in this model is included in Section IX.

III. Approach

Aircraft technologies will be discussed by system, as broken down in a weight statement following SAWE RP-8A [9]. Five SAWE weight-reporting groups were chosen as the major systems that can be disrupted by new technologies in UAM: wing, rotor, propeller/fan installation, fuel system, and engine system. In each section, an understanding of baseline technology assumptions from previous research and development is given followed by potential research areas for the given system. These five system groups are followed by the other baseline technology assumptions and a discussion on how these future research areas could make an impact on this future transportation system. The subsequent sections of the document are organized according the the generic description given in the subsections that follow.

A. Baseline Technologies

The baseline technology assumptions that were used for the intial reference vehicles will be given in this section. A general discussion of state-of-the-art technologies may be found in Ref. [10], and the technologies selected for the baseline aircraft are generally those which are planned to have achieved technology readiness level (TRL) 5 by 2020 [11]. This includes technologies scheduled for demonstration in NASA, other government agencies, and industry, with a relevant example being the US Army Joint Multi-Role Technology Demonstration Project [12]. TRL 5 is generally considered the level at which a flight vehicle program may proceed to development of flight test articles and subsequent production, and therefore seems a rational threshold for vehicles which will be going forward into the flight vehicle construction and testing phase by the year 2020. Since there are many emerging propulsion technologies being pursued in the UAM vehicles, there will likely be lower TRL technologies that will need to be matured to TRL 6 with their integration in the flight test vehicle. We have included low TRL propulsion technologies in our reference vehicles, but have mitigated the overall risk by relying on more mature technologies in structural systems. While aircraft with many simultaneous new inventions have indeed been successful in the past and are characteristic of many UAM industry designs, we are interested in separately identifying the opportunities and challenges particular to new approaches in vehicle systems and propulsion technology.

B. Future Research Areas

These sections of the paper look to explore selected additional technologies which have not yet been incorporated in RVLT UAM concept vehicle studies, but which we are interested in investigating in the future.

Urban Air Mobility has been enabled in part by advances in electric propulsion and autonomy, and as such these technologies have been the focus of current development. In particular, design for efficiency and for acoustics has not played a central role in the development of many N+1 UAM vehicles. For example, the RVLT lift + cruise concept, which uses separate lift and cruise propulsors, must accept weight and drag penalties associated with utilizing propulsors that are only used for specific segments of the flight. N+2 UAM aircraft need to reach far beyond these initial capabilities.

These sections discuss selected technologies specifically which may improve UAM vehicle capabilities, first by describing past and recent developments in the technology, and then discussing how this technology may provide benefit to UAM. Urban Air Mobility is an emerging market, and some of the hurdles which must be overcome to bring this new transportation modality to market are yet to be recognized. One of the technologies mentioned in these subsections may be an enabling technology for scaled operations. For example, it is possible that UAM operations will be severely restricted by acoustic thresholds imposed by cities. As such, there may exist a case where only the quietest of vehicles is able to operate, perhaps giving reason to accept reduced vehicle performance in return for reduced noise.

The final application of these technologies will come down to tradeoffs made by the designer. It is important to consider all technology options at this stage, to ensure that assumptions and decisions made in key design areas, such as vehicle design, airspace planning, network planning, infrastructure planning, and energy storage, take these advanced technology options into consideration and can make informed decisions as to which technologies may be restricted by the decisions made today and in the future.

IV. Wing Group

A. Baseline

The technologies for wing construction embodied in the baseline designs are carbon composite construction, with sandwich panels and co-cured or bonded construction. Limited use of secondary fasteners are expected in the wing construction. Fairings and secondary structures are manufactured from composites as well. Intermediate-modulus carbon fibers and autoclave processing has been assumed for the materials, as these are available in commercial quantities today and in widespread use.

The primary torque box and spar caps are co-bonded and constructed from tailored unidirectional or woven carbon composite in layers which are primarily selected for stiffness of the wing assembly. For the RVLT N+1 reference vehicles, the wing weight has been parametrically assigned, with technology factors used to capture the impact of composite construction relative to the largely aluminum construction in the empirical regression data set. Structural dynamics will drive the stiffnesses required, and more detailed comprehensive analysis with finite element analysis of candidate composite layups will be used as the designs are refined. An example of this type of construction is the V-280 Valor aircraft of the Joint Multi-Role Technology Demonstration (JMR TD) [13], which is presently demonstrating TRL

6 in flight tests.

Wing airfoils are expected to represent good passive-control technology, with partial laminar flow, benign stall, and with benign degradation of performance in the presence of contaminants. For instance, the reduction in the extent of laminar flow due to rain, ice, or other contaminants is not expected to be accompanied by sudden separation and loss of lift. NASA general aviation airfoils such as the LS(1)-0421 airfoil have been assumed to be representative wing airfoils for the speeds and operating regimes of these aircraft [14].

B. Research Area: Deflected Slipstream

1. Description

Deflected slipstream techniques to enable vertical takeoff and landing (VTOL) entail the deployment of wing flaps to turn the slipstream of propulsors downward, such that the resultant force acting on the aircraft is vertically upwards. Once airborne, flaps are retracted for cruise. A key benefit of this technology is that there is no need to either use separate lift and cruise propulsors, or to mechanically tilt the wing and/or propulsors, to enable VTOL operations with wing-borne flight in cruise.

2. Background and Past Research

Deflected slipstream flaps for VTOL were investigated in the 1950s and 1960s. In the 1950s, a large number of wind tunnel tests were conducted at the Langley Aeronautical Laboratory. Kuhn [15] investigated the flow turning effectiveness of a propeller-blown wing with many different flap and slat configurations. Kirby [16] investigated the use of biplane wings with double slotted flaps. Lastly, Tosti [17] investigated stability and control of a four-propeller aircraft model which utilized a full-span flap and a cascade of eight retractable vanes above the wing. Example pictures of these investigations are shown in Fig. 3. These investigations showed:

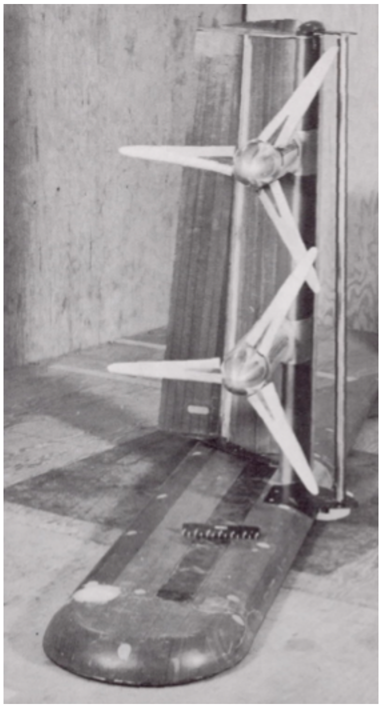
- Resultant forces of 64°-90° above the propeller thrust axis were achieved, with a magnitude of 80-90% thrust, depending on configuration and ground effect.
- The resulting pitching moment of the deflected slipstream concepts were large. Pitching moment was reduced by lowering the thrust axis to one-quarter diameter beneath the wing leading edge, and/or by applying an auxiliary vane above the wing.
- Wing end plates improved flow turning angles and resultant lift force.

The Ryan VZ-3 deflected slipstream vertical and/or short takeoff and landing (V/STOL) aircraft, pictured in Fig. 4(a), was developed by the Ryan Aeronautical Company for the U.S. Army and flight tested by NASA Ames Research Center between 1957 and 1963 [18]. This aircraft used double slotted flaps with wing end plates, and a turbine engine to drive two counter-rotating propellers, one ahead of and one below each wing. The aircraft had both a tricycle landing gear and tailwheel; when on its tailwheel the propeller axis and wing were pitched nose-up to improve thrust and flow turning. Differential propeller pitch was used for low-speed roll control. Low-speed pitch and yaw control used a thrust diverter in the tail, which relied on engine exhaust so was effective only in high power situations. Flight tests achieved an airspeed range of 0 to 80 kts in upper air; however adverse ground effects, associated with recirculation of the propeller slipstream, prevented operation at heights less than 15 ft and speeds less than 20 kts. Installation of leading-edge slats markedly improved descent characteristics: without them, slow, steep descending flight appeared infeasible due to wing stall, even with blown wings at high power. Hover in ground effect was achievable with a small headwind, but gusts and cross-wind conditions caused abrupt pitch, roll and sideslip which were difficult to control. In summary, the VZ-3 demonstrated good STOL characteristics, but a number of difficulties were experienced for VTOL operations.

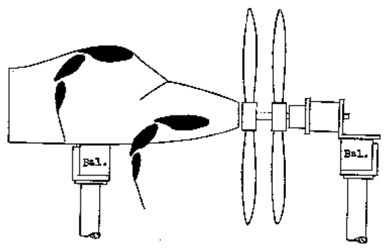
Two other deflected slipstream V/STOL aircraft, the Fairchild VZ-5 and Robertson VTOL, were built in the late 1950s. Both made tethered flights, but development was not pursued [19]. The VZ-5 used four wing-mounted propellers, and two separate tail rotors for pitch and yaw control, shown in Fig. 4(b). In both of these cases, the wing included double slotted flaps and a leading-edge slat, with the aircraft landing gear used to set the aircraft at an increased angle of attack on the ground.

3. Current Research and Level of Development

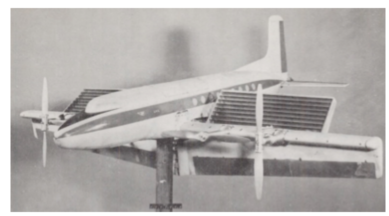
Deflected slipstream aircraft are not in use for VTOL operations today. However, the application of recent technology advancements such as distributed electric propulsion (DEP) and improved control systems may mitigate some of the problems seen previously, to enable deflected slipstream VTOL operations. For example, DEP allows for high P/W



(a) Example wind tunnel experiment by Kuhn [15].



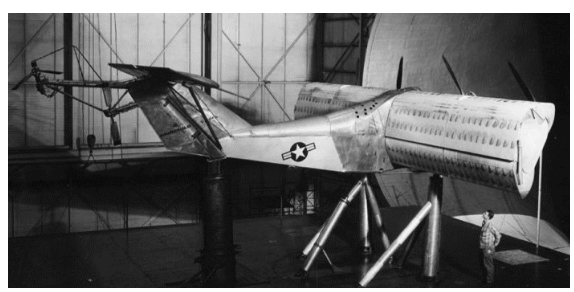
(b) Test configuration used by Kirby [16].



(c) Aircraft model used by Tosti [17].

Fig. 3 Examples of wind tunnel tests conducted at Langley Aeronautical Laboratory in the 1950s.

(a) Ryan VZ-3 deflected slipstream V/STOL aircraft, shown with slaps fully extended and with full-span leading edge slat installed [18].



(b) Wind tunnel test of the Fairchild VZ-5 [20].

Fig. 4 Historical deflected slipstream aircraft.

electric motors that can be independently controlled and will allow tail control power independent of wing blowing power [21]; improved control systems will enable better gust reaction; and advanced materials will allow improved airfoil shapes and also enable a biplane or tandem wing configuration, which offers pitching moment benefits. Improved computational aerodynamic solvers enable dramatically improved analysis of a blown wing in hover and transition flight.

4. Application to UAM

Deflected slipstream aircraft may remove the need to either mechanically tilt the wing or propulsor, or use separate lift plus cruise propulsors, to achieve VTOL UAM. This could provide benefits in cruise efficiency, weight, noise, reliability, and maintainability, and offer safer transition characteristics.

Additionally, deflected slipstream vehicles can be used as V/STOL vehicles. Optional STOL capabilities may allow increased operating range, or increased payload, thus enabling UAM aircraft to reach a broader market; for example, routes with an origin and/or destination in rural or suburban areas that may not be reachable with the limited range of near-term VTOL UAM concepts.

5. Future Forecasts

The ultimate reason for using deflected slipstream techniques is to enable efficient wing-borne cruise flight with VTOL or V/STOL capabilities, without requiring mechanical rotation of the wing or propulsor to transition between vertical and cruise flight. Improvements in deflected slipstream techniques may be achieved through incorporating additional aerodynamic techniques in the wing design. For example, wing design in previous cases included double slotted flaps for flow turning, with leading edge slats to improve descent characteristics. Flow turning and operating characteristics may be enhanced through the integration of other techniques, such as:

- Passive flow control techniques, such as vortex generators and wing fences; however, these must be suitable for all phases of flight
- Active flow control techniques, such as blowing and suction, can be used to improve flow attachment and can be varied for each phase of flight, thus improving controllability
- Different aircraft wing configurations, such as biplane, tandem wing, canard, or oversized tail, to improve pitching moment characteristics
- Number and size of propellers: for example, ground effect caused by recirculation of the propeller slipstream occurred at a height of 1.5 propeller diameters for the VZ-3 [18]; the use of many smaller-diameter propellers may reduce ground effect issues, while blowing a greater wingspan. However, this may affect flow turning effectiveness due to smaller diameter propellers.

One such active flow control technique is the use of co-flow jets. Co-flow technology combines blowing at the leading edge and suction at the trailing edge of the wing, through the use of a micro-compressor embedded in the wing. This is currently under investigation by Zha and has shown promising computational fluid dynamics (CFD) and wind tunnel results for an unblown wing in a 4.8 m/s freestream, achieving a maximum lift coefficient of 8.6 [22]. Further CFD and wind tunnel tests of a static co-flow wing in a propeller slipstream will confirm the potential of this technology to benefit VTOL operations.

Many of the aforementioned techniques can build upon previous development of powered lift techniques for STOL operations [23], and on current investigation of blown wings, for example NASA's X-57 aircraft [24]. These advanced technologies may also improve noise characteristics. However, there is a tradeoff between complexity and performance, which must be considered by the aircraft designer in light of the design concepts of operations. Additionally, some of the techniques listed above may vary with Reynolds number, and scaling effects; for example, co-flow will only be applicable in vehicles where a micro-compressor can be installed into the wing.

V. Rotor Group

A. Baseline

The technologies for rotor blade construction embodied in the baseline designs are carbon composite construction, with lightweight cores and co-cured or bonded construction. The leading edges incorporate erosion strips to provide protection against particles (including rain water, which can rapidly erode an unprotected composite rotor blade). The leading edges also include passive and active anti-ice treatments, including coatings and heating elements, except in the case of the Lift+Cruise.

Rotor airfoils are representative of good passive control airfoils for rotors which have been in existence since the mid-1980s. The VR-12 (Boeing) for the working section and SSC-A09 for the tip have been used for calculating rotor performance [25]. Some tip sweep and taper has been included in all but the Lift+Cruise aircraft, where the low aspect ratio makes those features less likely to be useful. Some extensively laminar flow airfoils have been developed in the recent past with impressive performance, however, the tempo of flight operations and the extensive time at low altitudes will likely result in blades which are likely to suffer from surface contaminants, so we have elected not to take credit for this performance in the RVLT N+1 concepts.

B. Research Area: Low-noise Edgewise-flight Rotors

1. Description

A number of noise sources have been identified in the extensive use of single main rotor helicopters, including operation near urban populations. As a result, there has been extensive research into operational and technological mitigation of noise. The main rotor is a major source of noise, and when present, the tail rotor is also a potentially major source. There are known technologies and operational adjustments which can significantly reduce the noise footprint of helicopters. The methods and technologies which reduce the noise of conventional helicopters are also applicable to many other types of vehicles with edgewise-flight rotors.

Specific technologies we suggest considering for edgewise-flight rotors are:

(a) Variable rotor speed operation, specifically reducing tip speed when practicable to reduce compressibility-induced noise
(b) Higher harmonic control (HHC) and individual blade control (IBC), which offer the ability to change the physical placement of blades with respect to tip vortices generated by other blades while maintaining trim, and thus eliminating blade vortex interaction (BVI) noise
(c) Blade shaping, which can change the physical placement of blades with respect to tip vortices, thus eliminating BVI noise
(d) Blade airfoil and planform, which can reduce noise due to thickness and compressibility
(e) Elimination of a tail rotor by use of a NOTAR (no tail rotor)-type solution, which eliminates the production of tail rotor blade noise and also eliminates BVI interaction between high-speed tail rotor blades with vortices from other blades (either from the main or tail rotor)
(f) Trim state modification by development of X-force by some aerodynamic mechanism, which can change the trim state of the vehicle in a manner which, especially in descent, causes the convection of the wake to change relative to the physical placement of blades such that tip vortices generated by other blades no longer interact strongly with the blades, and thus eliminating BVI noise
(g) Operational adjustments to flight paths to reduce objectionable noise generation and also reducing the time spent in proximity to observers while generating noise

2. Background and Past Research

Noise reduction of helicopters has been an important area of research for decades. The guidelines for military secrecy have limited the dissemination of data regarding the acoustic signatures and technologies for mitigation of noise, especially in specific helicopters which have military variants.

(a) Reduced tip speed has been demonstrated for rotor noise suppression in analysis, wind tunnel, and flight since at least the 1960s.
(b) Higher harmonic control and individual blade control have each been demonstrated in analysis, wind tunnel and flight; these demonstrated improvements have been summarized by Ref. [26] in table 18.3.
(c) Blade shaping for acoustics has been performed fairly recently, notably by Eurocopter in the 2000s with the BlueEdge blade. The demonstrations include analysis, wind tunnel, and flight test [27].
(d) Tip shaping and airfoil selection to reduce compressibility has been used at least since the 1950s, with swept tips, thin airfoils, and chord variation all employed. The demonstrations include analysis, wind tunnel, and flight test.
(e) NOTAR has been studied, primarily by Hughes and McDonnell Douglas in analysis, wind tunnel, and flight test in the 1980s and 1990s. Certification testing upholds the conclusion that the NOTAR approach yield lower noise as measured by the certification metrics than similarly-sized rotorcraft.
(f) X-force trim has been studied in the mid-1990s through mid-2000s [28] [29]. The demonstrations include

analysis, wind tunnel, and flight test.

(g) Operational mitigation of helicopter noise has been the subject of ongoing research since at least the 1960s, with a more recent emphasis on civilian operations. The demonstrations include analysis, wind tunnel, and flight test.

3. Current Research and Level of Development

(a) Reductions of tip speed are currently being examined in a number of UAM vehicles. TRL is 9 for helicopters, and less than 6 for other UAM vehicles.

(b) Higher harmonic control is currently being investigated in ground test in the US Army JMR TD program with Karem Aircraft. TRL is 9 for helicopters, and less than 6 for other UAM vehicles.

(c) Current research continues in blade shaping, including current RVLT [Doug Boyd] analytic design of rotor blades. TRL is 9 for helicopters, and less than 6 for other UAM vehicles.

(d) Current research in tip shaping is limited; this is generally viewed as a well-understood area. TRL is 9 for helicopters, and can probably be considered above 6 for other UAM vehicles.

(e) Little current research is going on for NOTAR vehicles, primarily due to the limitations of the resources of the industry developer of the technology, and its higher cost and weight than standard tail rotors. TRL is 9 for helicopters, and less than 6 for other UAM vehicles.

(f) X-force trim is not currently undergoing active research, because the weight and cost has not been competitive with standard helicopters. TRL is 6 for helicopters, and less than 6 for other UAM vehicles.

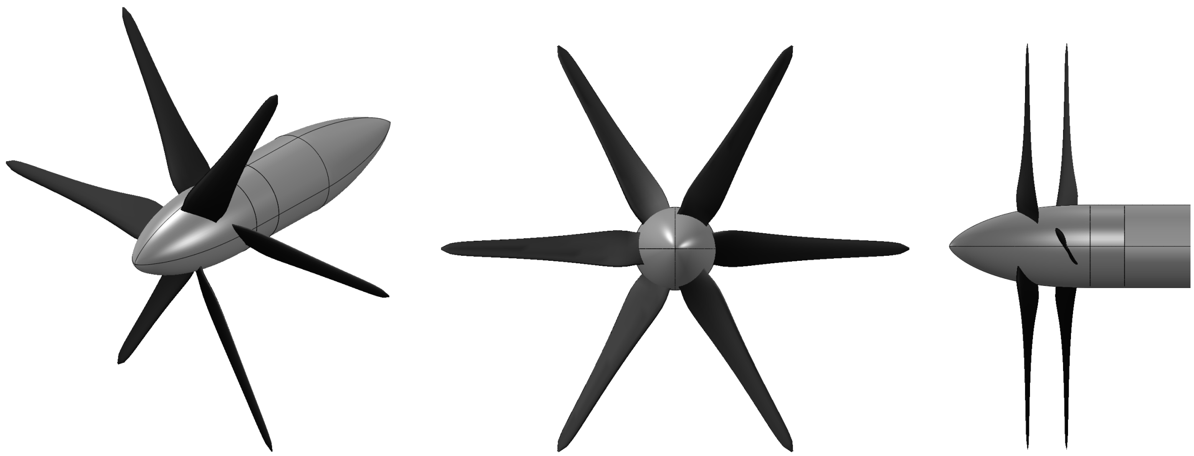
(g) NASA has been looking at real-time feedback for operational mitigation of noise for observers on the ground by the use of predicted noise based on the current and future flight conditions and control inputs [30]. NASA and the US Army have been collecting and analyzing flight test data of various helicopters [31], and this work is feeding the Helicopter Association International (HAI) fly neighborly program, with basic rules of thumb which have been distilled into a single page of recommendations. These recommendations have been vetted by the U.S. Department of Transportation Volpe Center and NASA. The operational methods for reducing noise will be considered as well as the existing certification standards for optimization metrics. TRL is 9 for helicopters, and less than 6 for other UAM vehicles.

4. Application to UAM

Ordinarily, certification standards would be the dominant noise consideration, but given that urban air mobility operations will involve both more operations in proximity to large populations and entirely new routes and destinations, we have the opportunity to use operational choices to produce less annoyance for UAM vehicles. All of these single main rotor helicopter technologies are applicable to UAM, since the single main rotor helicopter is in use for UAM today. The biggest challenges are further increasing complexity of helicopters and therefore cost and reliability. Weight growth with these technologies is a concern, but since helicopters are the lightest known solution for UAM, there is significant weight budget to work with when comparing helicopters to another vehicle type.

5. Future Forecasts

Given the demonstrated levels of noise reduction for edgewise helicopters with a single component technology, it is possible to predict that several different noise sources may be simultaneously reduced in a purpose-designed aircraft. However, care must be taken to understand the mechanism of sound generation, propagation, and character which is being modified by the suppression approaches to avoid "double-booking" improvements. For instance, a slowed-rotor with BVI elimination in descent and cruise and the elimination of an exposed tail rotor, might be expected to achieve 3-6 dB reduction from each of these sources, but that does not necessarily mean that these can be linearly summed. Nevertheless, it is probably reasonable to expect more than 6dB reduction is possible from the current noise levels of the MD 600N for a 6-person aircraft in descent and terminal operations, which is likely to dramatically increase the public acceptance of such a vehicle, given the already-low overflight noise of the MD 600N.



(a) Isometric view (b) Front View (c) Side View

Fig. 5 Notional stacked propeller consisting of two, three-bladed propellers.

VI. Propeller/Fan Installation

A. Baseline

For the baseline aircraft, propellers are of composite construction, with propeller-style hubs of either fixed or collective-pitch. General tip shaping is for performance, not specifically for noise. As with the rotors, tip speed is selected as low as practical to reduce the acoustics generated by high-speed flow at the tip.

B. Research Area 1: Stacked Propellers/Rotors

1. Description

"Stacked" propellers or rotors exist when multiple propellers or rotors are placed axially out of plane with one another, and rotate in the same direction, about the same axis. A notional stacked propeller consisting of two three-bladed propellers is shown in Fig. 5. In this example, the stacking is azimuthally symmetric.

Both rotors and propellers have been tested in stacked configurations in the past. For the purposes of this discussion, the difference between a rotor and propeller is defined by the mode of operation: a rotor is operated predominantly in hover or edgewise flight; whereas a propeller is operated predominantly in axial forward flight.

2. Background and Past Research

Stacked rotors and propellers have been tested in the past to accomplish various goals. One of the first historical uses of stacked proprotors was developed in the late 1930s and early 1940s for the Vought V-173 "Flying Flapjack" [32], to permit teetering of blades to relieve high cyclic loads during high power, high angle of attack, V/STOL operations. A similar configuration was used for the same purposes for the NASA Puffin personal air vehicle concept, and CFD studies also showed increased efficiency of about 4% and a slight reduction in noise of less than 1dB, relative to an in-plane propeller [33].

The Hamilton Standard Variable Camber Propeller [34] was developed in the 1960s, and used stacked propellers as analogous to a multi-element wing through the use of two rows of variable pitch propellers that could be aligned to optimize static or cruise performance. Static thrust performance was improved, but cruise performance did not match conventional propellers.

In the 1990s, Dobrzynski investigated unequal blade spacing to reduce propeller noise in forward flight, and used stacked propellers to overcome the challenges of balancing asymmetrically spaced propellers. Studies focused on higher subsonic to transonic Mach numbers, and achieved noise reductions of about 4 dBA, with no significant effect on aerodynamic performance [35].

Rozhdestvensky [36] investigated stacked rotors in the 1990s, by the name of 'scissors rotors' for use as helicopter tail rotors. Rozhdestvensky found improvements in rotor efficiency and found broadband noise benefits in flight.

3. *Current Research and Level of Development*

There are limited examples of stacked rotors and propellers in operation today. The Apache tail rotor uses two stacked, unequally spaced, two-bladed teetering rotors, similar to the V-173. Unequal spacing was initially selected to improve mechanical clearance, and was also found to reduce the 4/rev component of tail rotor noise [37]. Additionally, propeller manufacturer IvoProp uses stacked propellers in an 'X' configuration to increase available thrust [38]; these propellers are used on powered parachutes, and a similar IvoProp stacked propeller has also been flown on a BearHawk aircraft to improve STOL performance [39].

In the last decade, there has been renewed interest in the use of coaxial rotors for high-speed rotorcraft. Uehara and Sirohi [40] conducted static tests of two stacked two-bladed rotors, and found that stacked rotor performance was highly dependent on phase angle offset between the top and bottom rotors. When the lower rotor lagged the upper rotor by 10 degrees, a 4% performance gain was seen compared to a contra-rotating rotor. Ramasamy, on the other hand, tested two stacked three-bladed rotors and was not able to find a performance gain for the stacked rotor relative to a contra-rotating rotor [41].

Small UAV-scale stacked rotor configurations have recently been tested in static conditions at NASA Langley Research Center, and initial experiments have shown performance benefits of 6 to 7%, with considerable reductions in broadband noise, relative to a coplanar rotor with the same number of blades [42].

Past research indicates that stacked rotors and propellers have the potential to improve performance and/or noise characteristics relative to conventional rotors and propellers; however, there is not yet conclusive evidence as to the underlying aerodynamics enabling these benefits, which appear to be highly dependent on wake interactions. Computational analysis tools are likely to assist in understanding the underlying aerodynamics behind stacked rotors and propellers. CFD predictions [43] have been shown to trend in common with stacked experimental results in hover [44] and are likely to be useful in wake analysis. Two low-order tools have also been tested for stacked configurations. Bhagwat [45] used the U.S. Army's Rotorcraft Comprehensive Analysis System to model Uehara and Sirohi's experiment [40] and showed interesting analysis of the wake, although no formal validation of the tool was completed. Initial investigations into the use of FlightStream®, a commercially available vorticity flow solver [46], are documented in Ref. [42], and have instigated a number of developments to improve the induced velocity model used in FlightStream®.

4. *Application to UAM*

Past and recent research shows that considerable performance and/or acoustic benefits are achievable through the use of stacked rotors and propellers, and that benefits are applicable to all size scales of UAM vehicles. UAM operations are expected to be VTOL, which requires notoriously high power; the performance improvements achievable through the use of stacked rotors will enable equivalent reductions in vehicle maximum power and vehicle energy usage, or increases in payload capacity. UAM operations may also be severely restricted by noise thresholds imposed by cities; stacked rotors and propellers may assist in noise reduction, particularly broadband noise.

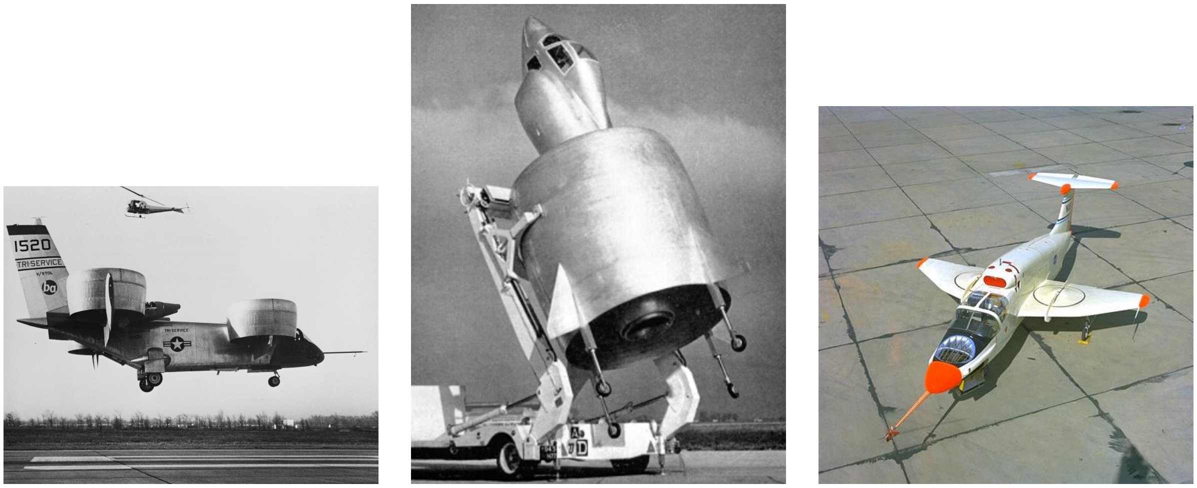
5. *Future Forecasts*

Further research is required to understand the full extent of the performance and acoustic benefits achievable through the use of stacked rotors and propellers. None of the research to date uses particularly complex stacked geometries: experiments tend to only vary 1-2 parameters, and yet they already show worthwhile performance and acoustic benefits. Further research to deduce the underlying physics causing these benefits, and improved modeling and analysis capabilities, are expected to enable design optimization and may bring benefits greater than those seen thus far. Equally, there is sufficient evidence already that a simple stacked rotor or propeller configuration may be applied to a specific aircraft configuration today, and may be tested empirically to obtain a performance and/or acoustic benefit. Much of the research into stacked configurations to date has been conducted on rotors in static conditions. It is important that further research is conducted into the performance and acoustic characteristics of rotors in edgewise flight, and of propellers.

C. Research Area 2: Ducted Propeller

1. *Description*

A ducted propeller/fan is a propulsion system that consists of a propeller mounted within a duct. This arrangement allows for the tip vortices that are typically shed from the tip of the propeller to be significantly reduced thereby



(a) Tilting duct: Bell X-22.[50]

(b) Coleopter: SNECMA Coléoptère [51].

(c) Lift fan: Ryan XV-5B [52].

Fig. 6 Historical ducted propeller aircraft.

increasing the thrust produced. This reduction of the tip vortices as well as general shielding from blade noise should also provide an overall reduction in noise levels. This mechanism has various use cases; for this report, we will focus on the "tilting duct", "coleopter," and "lift fan" as the typical variants for VTOL applications. The tilting duct is a ducted propeller that tilts from vertical to horizontal when transitioning from hover to cruise. Coleopters are tailsitter vehicles where the fuselage is placed in the center of a ducted propeller. Lastly, a lift fan integrates a ducted propeller into the wing or fuselage of the vehicle.

2. Background and Past Research

To better comprehend the description above, examples of past designs utilizing this technology are shown in Figure 6. All three of the designs shown were developed in the late 1950s and early 1960s.

The most successful of the three aircraft, the Bell X-22, flew as a test aircraft from 1966 through 1988 with over 500 test flights. After demonstrating that it was able to be controlled with relative ease, the aircraft was used to test sensors and instrumentation for various other V/STOL attempts. In their brief summary of the X-22, Jenkins, Landis, and Miller deemed that: "the ducted-fan configuration itself proved quite workable, although it has not been selected for any further aircraft to date [47]."

The SNECMA C.450 Coléoptère is the most successful coleopter to date. It was built in 1958 by Nord Aviation. It flew from April to July of 1959 completing nine flights. Tests one through five focusing on hover, while test six through eight attempted to understand transition. Flight nine transitioned from hover to forward flight, then back to hover. However, the vehicle did not have a successful landing. As mentioned by Hirschberg, Muller, and Rocher [48], the improvement in early-warning systems and long range surface to air missile systems made the role of this concept no longer necessary, which does not preclude the potential of the concept.

The Ryan XV-5 had two turbojet engines that were pneumatically connected to two 62.5 inch wing lift fans and one 36 inch lift fan for pitch control. To help control the vehicle in hover, each lift fan was equipped with moveable vanes that could vector thrust from 7 degrees forward to 45 degrees aft. The XV-5A flew for the first time in July 1964 and a modified version (XV-5B) last flew in January of 1971. Ronald Gerves, one of the test pilots of the XV-5 concluded that this vehicle was "proved that... lift-fans are robust and easy to maintain and operate [49]."

3. Current Research and Level of Development

There is significant current research in the realm of UAM and UAS for tilting duct concepts. Coleopters have seen minimal research and development interest in recent years. The most significant research and development in the area of ducted propellers is the F-35B Lightning II or Joint Strike Fighter. This aircraft uses a lift fan to achieve a short takeoff/vertical landing. It reached initial operational capability in July of 2015 and operational testing of the aircraft is still underway for various countries including the US, UK, and various other Nations.

4. Application to UAM

Tilting duct and lift fan concepts have garnered significant interest in the UAM field. The most notable concepts that currently feature this technology includes: AgustaWestland, Aston Martin, Bell, and Lilium [53]. There are significant advantages for commercial UAM opportunities that include but are not limited to: increased terminal safety, passenger acceptability, reduced noise, and reduced operating costs if designed properly. With this technology being adopted by several companies worldwide, there must be a concerted effort to better understand how this technology will apply to future commercial operations.

5. Future Forecasts

Ducted propellers will be a prominent technology on several future UAM vehicles. The potential for electric propulsion to influence the design and ease integration challenges of tilting ducts and lift fans is being realized. Coleopters/tailsitters offer extremely difficult design challenges and therefore high risk for current investors and start-ups. However, the research that was completed on various coleopter designs should help guide the potential for the application of this variant in future N+2 UAM designs.

VII. Fuel System

A. Baseline

In our interpretation of SAWE RP-8A guidance, the fuel system includes batteries and wiring because other energy sources and means of distribution such as fuel tanks and plumbing are placed in this category. For the baseline reference vehicles, the particular text below is a good summary:

"The baseline designs use an installed battery specific energy of 400 Wh/kg. Typical Li-ion battery discharge characteristics are used to calculate the battery efficiency. The internal resistance reduces efficiency at high discharge rates. Margins for maximum charge and discharge are established to prolong battery life (in terms of discharge-charge cycles): charge to within 5–10% of full capacity (depth-of-discharge 0.05–0.10), discharge to 15–20% capacity (depth-of-discharge 0.80–0.85). Current delivery limits for cells are specified as a C-rate (capacity/hr). The convention for the present designs is that the battery capacity refers to the usable energy, with the pack specific energy accounting for minimum and maximum depth-of- discharge limits. (Alternatively, the battery capacity could be increased above mission requirements to account for unusable energy, and the missions started at less than full capacity to reflect charge limitations.) Even with a high maximum burst discharge capability (maximum power), discharge currents must be limited to 2–3C for good battery life. The installed specific energy is reduced by packaging and conditioning requirements, including thermal management systems [4]."

B. Research Area: Solid Oxide Fuel Cell with Liquefied Natural Gas

1. Description and Current Research

For our baseline designs, 400 Wh/kg was used. However, the lithium-ion battery packs for the current X-57 test vehicle provide only 120 Wh/kg at the pack level. To reach 400 Wh/kg with a lithium-ion chemistry while still maintaining the high-level of safety required for a flight-critical component is unlikely in the near future. Therefore, Kohlman and Patterson have used a system-level model, that will be described in greater detail in Section IX, to conclude that a solid oxide fuel cell (SOFC) with liquefied natural gas (LNG) may provide a beneficial alternative [8].

Based on their analysis, a SOFC powered by LNG could result in lower energy cost (large contributor to operating cost), longer range, lower CO2 emissions, reduced noise and vibration, and lower infrastructure development costs. These are typical results from a systems analysis report, but these will likely not be the driving market considerations in determining what vehicle will be best to operate in this unique transportation system. Therefore, their model focuses on the transportation system as a whole and is therefore able to conclude that this energy source will also enable much faster turn-around times. So in an industry that money is lost for every minute that you are not flying, this is an important factor that you can now account for much earlier in the design process.

VIII. Engine System

A. Baseline

There are many different propulsion approaches which have been assessed in the current reference vehicles and their excursions. The propulsion approaches include traditional turboshaft, reciprocating internal combustion engines, and electric motors, with various hybridization approaches considered. For each of these, there are common themes of a need to reduce the weight of the engines and motors in order to improve the practicality of UAM vehicles. Therefore, the research area below is simply choosing one that has potential for future improvement, which does not imply a lack of potential for radical improvement in other propulsion approaches. Engine noise, while annoying very near the aircraft, is generally not a dominant annoyance source for existing rotorcraft during climb, overflight, or descent, so the benefits are mostly from an overall system efficiency standpoint. There is indirect benefit to acoustics from improving weight efficiency, as smaller aircraft generally are quieter.

B. Research Area: Improved Turboshaft and Reciprocating Engine Weight Efficiencies

1. Description

Advances in materials, manufacturing, and design have the potential to reduce the weight of small engines. Historically, the research in this portion of the design space has been limited because the market has been small compared to larger VTOL and fixed-wing aircraft. Technology for additive manufacturing, in addition to new design layouts, when combined with the large size of UAM markets, can impact the design and economic assumptions which have been made.

For turboshaft engines, the engine technology in the baseline aircraft are representative of the work done in programs such as the Advanced Affordable Turboshaft Engine (AATE) and its successor, the Improved Turboshaft Engine Program (ITEP).

For reciprocating engines, we have considered existing aviation diesel engines. These suffer from fairly low specific power, but offer low fuel consumption. The diesel engine for our reciprocating excursion single-passenger quadrotor is based on the Austro diesel used in Diamond and other aircraft today.

Worth noting is the comparison to electric motors. There are many automotive electric motors and a few aviation electric motors existing today. Existing electric motors generally fall into two categories, based on their torque-to-weight ratio (Q/W). High Q/W motors in our existing database, like those produced by Tesla for automotive applications, have been the basis of the weight estimation. Bare motor weight tends to be the dominant fraction of the weight which would be book-kept as "Engine System" weight, but there is significant additional weight in the inverters and controllers and cooling for today's electric motors. We have assumed state-of-the-art in this regard for our baseline reference vehicles. In Europe, Pipistrel and Siemens each have aviation motors in current usage.

2. Background and Past Research

The AATE/ITEP technology has improved power/weight and specific fuel consumption (SFC) in the 1500 - 4500 shp size class, with SFC below 0.4 lb_m/hr/hp being demonstrated. This size class is larger than many of the vehicles envisioned for UAM. In the lower-power engine sizes, there has not been the same level of development, and there is opportunity to gain significant improvements, particularly with regard to specific fuel consumption, where values of above 0.6 lb_m/hr/hp are typical today.

Small reciprocating aero engine research has been limited, primarily constrained by the perceived small size of the market. For rotorcraft, general aviation engines have historically been used, as in the case of the Robinson R-22.

3. Current Research and Level of Development

There is currently some early-stage research regarding the use of recuperators, especially with the advent of metal 3-d printing, which may significantly reduce the previously-prohibitive cost of manufacturing the heat exchanger elements of the system.

There is limited research ongoing for 200-1000 shp turboshaft and small diesel motors, with regards to improving their specific fuel consumption and specific power, respectively. The existing efforts are mostly based on unmanned air vehicles, and have not been widely coordinated. The US Army in 2016 began looking for information under the Reliable, Advanced Small Power Systems (RASPS) technology project, in the range of 40-400 shp.

4. Application to UAM

For UAM, the weight of motors, engines, and their associated systems need to be reduced, and in the case of small turboshafts, the specific fuel consumption is a particular challenge. Our N+1 UAM reference designs range in power from 83 hp for the one passenger diesel quadrotor to 4730 shp for the 15-passenger turboelectric tilt wing. In the small size class of single-passenger transport, SFC for the diesel quadrotor is 0.38 lb_m/hr/hp, but the turboshaft is 0.87 lb_m/hr/hp. The small diesel specific power is 1.9 lb/hp, whereas the small turboshaft achieves 0.7 lb/hp. Simultaneous achievement of good specific power and specific fuel consumption is a challenge at the size of about 100 shp, but the payoff would be substantial. The electric motors handily beat both diesel and turboshaft in specific power, with about 0.38 lb/hp, distributed among 4 smaller motors (although the scaling is such that a single engine of about 100 hp would be essentially the same) [6].

5. Future Forecasts

We expect that there will be technology development in increasing the SFC of small turboshafts, perhaps with the use of recuperation to increase thermal efficiency. The penalty in weight for the addition of recuperation may still be low enough that these powerplants will be more efficient than today's diesels. The desire to use heavy fuels in UAV applications is a powerful driving force for the development of efficient small turboshafts, and there is good reason to expect the technology development will be funded by the US military, perhaps in partnership with NASA. It is unlikely that we will see SFC in the range of larger turboshafts, but values below 0.5 lb_m/hr/hp are not unreasonable to expect, with a small penalty in specific power for the introduction of an optimized recuperation system.

Small aviation diesels would benefit greatly from improvements to specific power, and there are some technology approaches with materials and design layout which may achieve some improvements in weight, while maintaining the outstanding specific fuel consumption. Funding for this research is not as clear; the military does see value in diesels as able to use the same heavy fuel supply, but the simplicity and robustness of turboshafts are hard to beat.

Once again, it is worth noting electric motors in comparison. Electric motors will likely continue to improve, with improvements in power electronics and thermal management being the biggest contributors to weight reduction. The current weight and simplicity of electric motor systems is attractive, and therefore there is less to gain from reduction in these systems compared to other parts of the aircraft. However, the difference in weight between heavy SOA electric energy storage and lighter fuel energy storage may lead to potential for interesting trade studies to realize the overall aircraft benefit.

IX. System Level Model

A system level model is necessary for the evaluation of technology impact on operational parameters such as direct operating cost (DOC), average load factor (ALF), and average wait time. In other words, implementing technologies that affect the efficiency of the vehicle (such as: deflected slipstream, improved turboshaft and reciprocating engine weight efficiencies, SOFC with LNG, and ducted propellers) should show a significant positive impact on these operational parameters. Unfortunately, it is difficult to quantify how an acoustic reduction (due to technologies such as stacked rotors/propellers and low-noise rotors for edgewise flight) will directly relate to operational parameters.

Selection of efficiency-related technologies can have a dramatic impact on energy costs, however there are many other areas that can be affected. For example, the acquisition cost of the vehicles can be a significant driver of DOC. Selecting a battery-based vehicle over a LNG-powered SOFC based vehicle can increase the mass of the vehicle which leads to increased cost. Selection of a deflected slipstream or ducted propeller over a tilt-wing concept can help reduce complexity and therefore mass but at significant production cost. A LNG-fueled vehicle may need to return to a refueling depot which can have an effect on ALF. With improved engine and hybrid-electric technology, the choice between battery and fuel changes the operational pace of the vehicles which may mean more vehicles are needed to meet demand or the average wait time will be adversely affected.

A. Vehicles

Selection of an appropriate sizing mission can have major impacts on the viability of certain technologies. In the case of VTOL aircraft, the duration of hover (or the highest power loading case) can make some configuration/propulsion system combinations infeasible or exceptionally expensive. As an example, a deflected slipstream aircraft with a low hover efficiency paired with a battery will struggle to meet a long duration hover requirement because the sized aircraft will grow rapidly. Such an aircraft may benefit from a hybrid-electric fuel-based power system instead.

Improvements that decrease airframe weight are generally positive as long as the vehicle level benefits to cost are preserved. The same can be said for technologies that improve efficiency. One of the trades that could be investigated is efficiency vs. weight for improved turboshaft and reciprocating engines when paired with a battery in a hybrid-electric propulsion system. In most cases, hybrid-electric technology can be improved at the cost of weight. This trade must be evaluated at the vehicle level. If for example, the aircraft is mostly battery powered, improving motor efficiency by increasing motor weight may offset far more battery weight for an overall net benefit.

B. Network

Operation of the vehicles within the intended network should also be modeled to evaluate technology impacts on parameters such as DOC, ALF, and average wait time. The selection between battery powered aircraft that must recharge after every flight will have very different operational characteristics compared to an LNG-fueled vehicle that must return to a depot.

Network modeling can also be used to evaluate different operational concepts such as new dispatch models. Dispatch model development can have major impacts on DOC, ALF, and average wait time and should be developed with consideration of the particular vehicle attributes.

X. Conclusions

NASA is developing Urban Air Mobility (UAM) concepts to (1) create N+1 reference vehicles that can be used for technology, system, and market studies, and (2) hypothesize N+2 UAM aircraft to determine high-payoff technology targets and future research areas that reach far beyond initial UAM vehicle capabilities. This report provided N+1 reference vehicles assumptions to document the current state-of-the-art, then high-payoff technologies that will enhance the capabilities of future N+2 UAM aircraft are identified.

For this report, five aircraft components were chosen as the major systems that can be disrupted by new technologies in UAM: wing, rotor, propeller/fan installation, fuel system (including batteries), and engine system (including motors). Future research areas discussed include: deflected slipstream concepts, low-noise rotors for edgewise flight, stacked rotors/propellers, ducted propellers, solid oxide fuel cells (SOFC) with liquefied natural gas (LNG), and Improved turboshaft and reciprocating engine weight efficiencies. A few conclusions can be drawn from this research:

1) Deflected slipstream concepts may remove the complexity of mechanically tilting the wing or propulsor while also providing optional STOL capabilities, which could allow for increased operating range, or increased payload, thus enabling UAM aircraft to reach a broader market.
2) There are known technologies and operational adjustments which can significantly reduce the noise footprint of rotors for edgewise flight. The methods and technologies which reduce the noise of conventional helicopters are also applicable to many other types of potential UAM vehicles with edgewise-flight rotors.
3) Past and current research in stacked rotors/propellers shows that considerable performance and/or acoustic benefits are achievable and that these benefits are applicable to all sizes of UAM vehicles.
4) The potential for electric propulsion to influence the design and ease integration challenges of tilting ducts and lift fans is being realized. There is potential for the application of coleopters in future N+2 UAM designs.
5) Based on the research of Kohlman and Patterson [8], a SOFC when paired with LNG can result in lower energy costs, lower CO2 emissions, and lower infrastructure costs than battery-electric systems.
6) There are some technology approaches with materials and design layout of turboshafts and/or reciprocating engines which may achieve some improvements in weight, while maintaining their outstanding specific fuel consumption.

While this report describes the benefits that may be achieved when single technologies are applied in isolation, it is important to consider tradeoffs when integrated onto the whole aircraft, such as potential changes in mass, drag, or complexity, or performance losses during certain mission segments. It is also just as important to consider how these technologies will impact operational parameters such as direct operating cost (DOC), average load factor (ALF), and average wait time. As these technologies develop, it will be valuable to quantify these tradeoffs. This is why future research and concept development will focus on ensuring that these technologies will result in a system level benefit.

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