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THE FUTURE OF ADVANCED AIR MOBILITY AIRCRAFT

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Abstract

Morgan Stanley recently predicted that the market for AAM aircraft could exceed $9 trillion annually by year 2050 [1]. This implies that AAM aircraft will be a major form of personal travel in the future.
This paper explores those AAM aircraft designs that are most likely to prevail in the personal travel market during the coming years:

- FAA certification challenges
- Payload that could capture the market
- Powerplant considerations
- Airframe and propulsion integration
- Deployment
- Funding and cost
- Epilogue

FAA Certification Challenges

Most AAM aircraft companies are concentrating on the development of five to seven person air taxis under the belief that the future personal travel market is going to be centered around ridesharing. However, ridesharing by AAM aircraft is unlikely to make up a significant portion of this future personal transport market any more than ridesharing by car does today. This is simply because travelers have different destinations and timetables. In addition, the traveler will need ground transportation at both ends of his or her trip, which makes airborne ridesharing even more impractical than ridesharing by car. Only 9 percent of workers carpool, which is a drop from 19.7 percent in 1980 [2].

Five to seven person AAM aircraft may compete effectively against higher payload helicopters on dedicated routes, because they are potentially quieter and safer. However, the logistics of handling a large number of flights per day from the top of a building or local Skyport is daunting if even possible [3]. This size aircraft would be looking for FAA certification under Part 21 in order to enter commercial services under FAA rule 135. FAA certification is a lengthy process even for a conventional design aircraft and can range from five to nine years [4]. AAM aircraft will be employing entirely new airframe designs and propulsion systems, which could make the timetable for FAA certification even more problematic. Developers are also concerned about the recent announcement that their aircraft will need to be certified under Part 21 rather than Part 23 as originally planned. Only the tilt rotor AW609 has ever attempted to be FAA certified under Part 21, which is an aircraft category called "Powered Lift Aircraft". The AW609 has been going through the FAA certification process for over 20 years as a commercial version of the military Bell XV-15, that first flew in 1977. Bell, Westland, and Augusta have spent many billions of dollars on its certification. A further concern is that Part 21 is not fully formulated and has never addressed batteries as a power source. This will make FAA certification even more challenging.

The FAA provides a special approval category for aircraft aimed at the recreational market which may make it possible to utilize variations of this special category as a way to gain experience with the unique nature of AAM aircraft and its application to the future personal travel market. The FAA's ultralight aircraft category could allow "fat" ultralight aircraft to operate at the higher weight allowed in some other countries. This category allows only one person and does not require a pilot's license or FAA certification. A second option would be to seek FAA approval under a modified form of the "Special Light Sport Aircraft (S-LSA) certification category which only needs to meet industry consensus standards. S-LSA aircraft are allowed to carry two people and require a pilot's certificate rather than a pilot license. Approval under

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either category would allow AAM aircraft to generate growing experience with their distributed propulsion, fly-by-wire controls and powerplant options, including engines, batteries, and hybrids. Following significant experience in the recreational application, the FAA could then accept a more general use in view of the FAA approval of the ultralight category, where the risk is only to the pilot. Two-passenger versions could follow.

Payload that could Capture the Market

For AAM aircraft to dominate the personal travel market by 2050 they will need to be as convenient to use as the automobile was at its best, while being able to travel much faster than future ground based transportation alternatives. This can only be accomplished if during VTOL the aircraft can reduce its size to approximately that of an automobile during its vertical landing, while meeting the local noise ordinance. At a minimum, this requires the wings to fold prior to landing in order to land at the city curb or a small parking lot.

Automobiles on average carry 1.5 passengers while 74.9 percent drive alone [[5]]. Therefore, a one-person AAM aircraft should make up the majority of the future personal travel market.

Advantages of a one-person AAM aircraft:

- May be viewed favorably by the FAA because only the pilot is at risk.
- Operating autonomously as an air taxi, it could replace the majority of automobile trips.
- Could achieve the equivalent of 70 passenger-mile per gallon of gasoline (equivalent) which is 50 percent higher than the average automobile per passenger-mile.
- Cost could be low enough following high production to generate significant private sales.
- Travel up to ten times faster than the average automobile speed of 18.6 mph [[6]].

Powerplant Considerations

In a best case analysis of AAM aircraft performance [[7]], batteries alone provided a range of 50 to 60 miles which is consistent with the range goals projected by the experienced aircraft companies, including Airbus, Wisk/Boeing, and Embraer. Startups including Joby, Lilium, and Beta Alia-250 all project much longer range and higher speeds that require batteries with a specific energy that may not be available in the near future. The referred to best case analysis assumes that the FAA will be willing to reduce the present reserve flight time for IFR flights from 45 minutes to 10 minutes. The maximum flight time of battery powered AAM aircraft is around 30 minutes, therefore if the FAA does not significantly reduce its present reserve flight time requirement, battery powered AAM will not be viable. The most important battery characteristic in determining range is its specific energy (Watt.hr/Kg). There are many variables involved in determining a battery's specific energy which is highly dependent on its operating history:

- Rate of charging and discharging
- Number of cycles
- Level of charge and discharge during each cycle
- Internal and external operating temperatures.

Consequently, battery specific energy will reduce over time in ways that could be very difficult to quantify. In effect, it is like not knowing how much fuel you have left. Despite a much lower battery discharge rate in electric cars there have been a number of spontaneous fires, contributing to nearly 600 deaths. A recent article in Bloomberg News titled "Air Taxis Keep Crashing, Burning into Flames in Testing Phase" [[8]] may

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be a cause for concern and lead the FAA to require a less hazardous battery chemistry to eliminate this potential problem.

A study by the AAA Foundation showed that the average automotive trip is 29.6 miles with most of those miles by personal vehicle. A one person battery powered aircraft could be a candidate to effectively provide this trip if it is small and quiet enough to land almost anywhere. However, if after nearly each trip it has to return to a facility to be charged or swap batteries, the inconvenience and lost time would significantly affect the Uber like trip costs. A hybrid version would reduce this concern while significantly increasing range. Cruise power would be provided by an engine while VTOL power would be provided by batteries. During the cruise mode, an on-board engine driven generator could recharge the small amount of energy expended during VTOL while the battery pack size could also be significantly reduced. An advantage of a hybrid version, in addition to increased range is that electric motors can achieve a maximum short term power output of over 7HP per lb. (two minutes from cold) which could reduce the installed weight of the motors by 70 percent. It is unknown whether the FAA is prepared to allow the electric motors to operate at their maximum power output during VTOL. If it does not, the hybrid approach becomes less attractive, and a better choice could be engines or batteries alone, depending on the importance of range and deployment.

Airframe and Powerplant Integration

The complexity of the airframe design is determined by whether the lift and cruise propulsion systems are separated or combined. Leading startups like Joby, Lilium, Archer, and Vertical Aerospace use designs that combine lift and cruise propulsion systems, while the experienced aircraft companies like Wisk/Boeing, Airbus, Embraer, and Honda use separate systems. When lift and cruise are combined the propulsion system may require many more critically moving parts to allow component articulation during transition between VTOL and cruise. In addition, the propulsion efficiency is reduced in both. The experienced companies accept the higher airframe weight and profile drag resulting from the use of separate propulsion systems in return for lower production cost, higher propulsive efficiency, and potentially easier FAA certification.

Aircraft Deployment

It is reasonable to assume that by year 2030 most AAM aircraft will be operating autonomously. This is consistent with the expectation that automobiles will be doing so far sooner despite their much more complicated operating environment. Once the software and electronically controlled hardware are proven to be reliable, the fatality rate per mile of AAM aircraft should fall below that of today's commercial airlines that are operating nearly autonomously. This should lead to a fatality rate that is less than one percent of that for the automobile [9]. Automobiles operate in a quasi-one dimensional roadway network versus two-dimensional off-road or over water versus three-dimensional travel by air. Each dimension increase greatly improves safety by increasing the operating distances between a given number of vehicles.

Funding and Cost

The leading start-up AAM aircraft developers (Lilium, Joby, Vertical Aerospace and Archer) have collectively raised billions of dollars through Special Purpose Acquisition Companies (SPAC). This has allowed them to undertake aggressive programs to bring their product to market. However, there are a number of unresolved issues regarding FAA certification of their products. These start-ups have been spending between $20 million and $50 million per month on designs that, for the most part, are substantially more complex than those undertaken by the experienced aircraft companies (Boeing, Airbus, Embraer, and Honda). In view of the five to nine years required to obtain FAA certification of conventional

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designs, these novel designs offered by start-ups could take even longer. Consequently, despite having more capital at their disposal for the development of any aircraft in history within this weight category, they could need to raise additional capital. Unfortunately, their stock prices on average, have fallen by over 80 percent in the months following their SPAC funding raise. The experienced aircraft companies are self-funding development at a much lower rate, consistent with resolving any FAA issues prior to investing heavily in production. While further behind in development of their simpler designs, the experienced companies are in the process of determining whether battery powered AAM aircraft are viable prior to committing to production. For example, Airbus's first prototype was a two-seat battery powered model called Vahana that underwent thousands of hours of flight testing. Airbus abandoned this earlier design in favor of a much simpler version for what should have an easier path to FAA certification.

A further concern that follows in part from the above comments is the projected cost of the AAM aircraft and how that could affect the market opportunity. The start-ups have all taken significant pre-orders with an average price of $4.5 million per aircraft. These are pre-FAA certification prices and are certain to rise post-FAA certification. Historically aircraft prices following FAA certification have been more than double the pre-certification offering prices. None of the following aircraft were nearly as novel as AAM aircraft powered by batteries using fly-by-wire controls and distributed propulsion.

Aircraft	ICON	AW609	Eclipse Jet
Pre-FAA certifcate price	$139,000	$10 million	$869,000
Post FAA certificate price	$369,000	$25 million	$2.5 million
Years from first flight to FAA certification	7 years	20+ years	5 years

In view of the revolutionary nature of battery-powered-AAM aircraft it is certainly possible that the versions proposed by the start-ups could have a sales price of $10 million each following FAA certification. A six-passengers helicopter like the Airbus EC335 sells for $5.7 million with a trip cost of around $3.5 per passenger-mile. The higher priced AAM aircraft could end up with a trip cost of $5 per passenger mile, or approximately three times higher than the cost of the Uber ground transport. Even at $3.5 per passenger-mile, helicopters are considered to be an expensive way to travel. In any case the inconvenience of airborne ridesharing will limit the AAM aircraft's ability to be a major alternative to ground transportation or see a lower unit cost without the benefit of economies of scale. By contrast, if one or two passenger versions can offer the convenience of the automobile as it existed before congestion reduced its usefulness, then economies of scale should reduce its cost in future dollars to that of today's quality automobiles.

Epilogue

- Battery powered AAM aircraft are only viable if the FAA substantially shortens its reserve flight time requirement. Reserve flight time has always been a fundamental requirement by the FAA.
- Ridesharing by air with five to seven passenger AAM aircraft will not succeed for the same reasons it failed with ground transportation, namely, travelers have different destinations and timetables. Furthermore, travelers will still have to find ground transport at both ends of their airborne trips.
- A one passenger AAM aircraft with the ability to land almost anywhere could surpass the 76 percent of all automobile trips now made by a sole driver.

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- The higher energy conversion efficiency of the battery powered aircraft at 86 percent versus the 30 percent energy conversion efficiency of engines is more than offset by the much higher weight and profile drag of battery powered AAM aircraft like the Cora under development by Boeing Wisk.
- The experienced aircraft companies have chosen to pursue simple designs, which may reduce the five to nine years required to achieve FAA certification for a new aircraft design.
- Hybrid versions where lift is provided by battery powered motors and cruise is powered by engines become less attractive if the FAA does not allow the motors to be temporarily overpowered for up to two minutes from cold during VTOL or in case of a powerplant failure.
- The experienced aircraft companies generally separate the lift propulsion system from cruise propulsion. This approach reduces airframe component articulation, improves propulsion efficiency, and may shorten the FAA certification timetable.
- The use of separate lift and cruise propulsion enables the lift motors to be mounted separate from the wings, which should permit the one or two passenger AAM aircraft to be small enough to land almost anywhere.
- Startups like Joby, Lilium, Vertical Aerospace and Archer have a lead over the experienced aircraft companies. However, this lead is likely to disappear as their complex designs are overtaken by the experienced aircraft companies with designs that could lead to a shorter FAA certification path.
- `The fire hazard presented by lithium-ion or lithium-polymer batteries is significant enough that the FAA is likely to require a different battery chemistry from that presently in commercial production.
- The ability to land anywhere requires wings that fold. This precludes the lift/propulsion system being mounted on the wings. The choice is then to mount ducted fans on the fuselage or the lifting motor/propellers on a separate support structure.
- The simplest path to FAA certification may be to seek FAA approval for a one-passenger version under the special categories reserved for recreational aircraft as a prelude to general use.
- Following extensive recreational use with battery power, fly-by-wire controls, and distributed propulsion, the FAA could be satisfied that safe operation has been established. Moving to a more general use could follow including approval to carry two people.
- Five to seven passenger AAM aircraft may cost substantially more than competing helicopters to manufacture. The resulting cost per passenger-mile could limit AAM aircraft use primarily on dedicated routes. As a result, they will not benefit from economies of scale as had been anticipated.
- The leading start-ups have underestimated the time required to achieve FAA certification. Their capital burn rate of $20 to $50 million per month reflects a totally unrealistic expectation of achieving FAA certification by 2024/2025. Consequently, additional capital will need to be raised. This will be difficult if not impossible due to the dramatic fall in their stock price and the emerging competition from the experienced aircraft companies.

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Design Characteristics of AAM Aircraft Powered by Batteries, Engines or Both			
Design Configuration	**Boeing/Wisk/Cora separate lift and cruise motors in a way that enables wings to fold prior to VTOL.**	**Skycar® 200 combines lift and cruise in a way that enables wings to fold prior to VTOL.**	**Hybridized Cora**
Number of persons	Two	Two	Two
Energy source	Battery	Engine/Methanol	Battery/Engine/Methanol
Energy consumption	0.35 Kwh per passenger mile at 110 mph. 0.95 Kwh at 200 mph.	0.42 Kwh per passenger mile at 110 mph. 1.03 Kwh at 200 mph.	Same as Skycar® 200 if battery capacity is significantly reduced
CO_2 emissions	Near zero if charged from renewable source.	Carbon neutral if fueled by renewable methanol.	Carbon neutral if charged from renewable source and fueled by renewable methanol.
Fire hazard	High with lithium-ion battery chemistry presently in use.	Low with bladder fuel tanks.	Requires lithium polymer batteries to tolerate the very high discharge rate if battery capacity is reduced.
Eventual cost/passenger	Five to seven passenger models could cost $1 million or more per passenger due to limited utilization and production. One to two passenger models could cost $100,000 or less per passenger following high volume production with widespread use.		
Noise	Quiet with low tip speed propellers. This increases drivetrain complexity.	Ducted fans allow various noise attenuation options. Unique engine technology required.	Quiet with low tip speed propellers during VTOL. Engine noise less critical at altitude.
FAA Certification timetable	Most problematic due to batteries and larger payload version.	Easier if begins with recreational market.	Uncertain due to not knowing the FAA's position on overpowering the lift motors.
Deployment	Most complicated because of the need to operate repeatedly from charging stations.	Least demanding if small and quiet enough to land almost anywhere.	Least demanding if small and quiet enough to land almost anywhere.
Cruise speed	110 mph	200 mph	Less than 200 mph due to higher profile drag and weight.
Range 10 minutes reserve	62 miles	500 miles	Less than 500 miles due to higher profile drag and weight
Range 30 minutes reserve	Not viable	460 miles	Less than 460 miles due to higher profile and weight.

Note: Energy consumption was taken from reference [7].

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ADDENDUM

Brief history of the author's efforts to create a VTOL capable AAM aircraft.

In 1957 Dr. Paul Moller received a diploma from the Southern Alberta Institute of Technology (SAIT) that qualified him as a certified airframe and powerplant technician. This was followed a year later by a diploma in Aeronautical Engineering from the same trade school. He then spent two years as an engineer at a Canadian aircraft company. In 1960 he was offered a fellowship at McGill University and graduated in 1963 with a M Eng. and a PhD in mechanical and aeronautical engineering. Upon graduation he was offered a teaching position at the University of California in Davis and became responsible for creating their Aeronautical Engineering program. While teaching he also began construction of his first VTOL aircraft in his garage. This single person aircraft called the XM-2 was flown before the international press in 1967. In 1968, he completed a two-person VTOL aircraft called the XM-3 and hovered it privately for potential investors. In the same year he and a partner undertook the following:

- *Created an S corporation called M Research (later expanded to become Moller International)*
- *Leased a 2,000 ft^2 facility*
- *Began development of the XM-4, which later became known as the Neuera 200*
- *Identified the Wankel rotary engine as the ideal powerplant for the XM-4*
- *Acquired a number of rotary snowmobile engines from Fictel-Sachs in Germany, the first company to put rotary engines into volume production.*

To meet its performance goals the Neuera needed an engine with a power to weight ratio substantially higher than that of the FS rotary engine. Artificial stability and fly-by-wire control system were also required. The R&D effort to undertake this development required a well-funded team. To raise the necessary capital, Dr. Moller together with a few supporters undertook a number of projects:

- *Developed the 40-acre Davis Research Park and constructed a 35,000 ft^2 facility.*
- *Created SuperTrapp Industries that became the leading aftermarket manufacturer of engine muffling systems in the world. ST was later sold to help fund rotary engine and airframe development.*
- *Completed a number of government-funded contracts that included the delivery of various unmanned aerial vehicles (UAV) to the US Army, Navy, and Air Force.*
- *Raised millions of dollars from private investors.*
- *In 1985 acquired the entire rotary engine production assets of Outboard Marine Corporation (OMC), the only US company to have put a rotary engine into volume production.*

Funding enabled Moller International (MI) to form a technical team of approximately thirty engineers and technicians that enabled its Rotapower® rotary engine to produce 70 percent more power for its weight than any existing aircraft engine. Concurrent with this engine development, artificial stability, and fly-by-wire control systems were also developed. Over the following years both the Neuera's engines and its stability and control systems underwent continuous ground and flight tests. On May 10, 1989 Dr. Moller piloted the Neuera before the international press. It was the first aircraft to introduce the concept of "distributed propulsion" which Dr. Moller had patented in 1971 (patent number 3614030). Distributed propulsion is now used by all of the over 250 different battery powered AAM aircraft being developed throughout the world. The Neuera is able to uniquely perform a number of tasks, like search and rescue, border patrol, crop spraying or as an all-terrain recreational vehicle; however, a true air-taxi requires a more ergonomic human interface, higher speed, and inherent aerodynamic stability during cruise.

In 1990 the development of the M400 Skycar® began. For technical reasons the Skycar® configuration has a higher disc loading (Weight/fan area) which demanded a further increase in the power to weight ratio. During the following decade this ratio was increased to over two, compared to a ratio of one for today's best aircraft engine. This enabled a demonstration flight of the M400 Skycar® in 2002 before the local press at MI's annual stockholder's meeting. However, it needed its Rotapower® engine to produce an even higher power to weight ratio in order to tolerate an engine failure at maximum gross weight.

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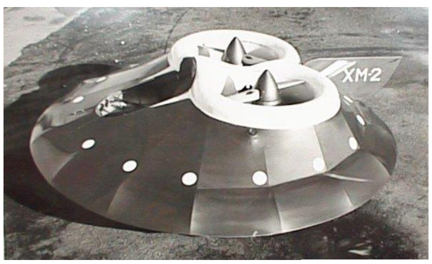
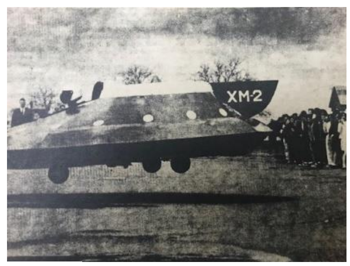
In 2002 MI exclusively licensed its affiliate company Freedom Motors (FM) to further develop, manufacture and distribute the Rotapower® engine for numerous worldwide applications that had arisen. Today, after two decades of engine development by FM, the Rotapower® engine has raised the power to weight ratio to over three, extended its life from 2,000 hours to over 20,000+ hours, enabled the efficient use of renewable methanol as a carbon neutral fuel and essentially eliminated exhaust noise. These and other technical improvements have led to six engine related patents now in process by FM following over a dozen earlier engine patents by MI.

The recent development of hundreds of prototype air-taxis powered by batteries encouraged Dr. Moller to review the state-of-art of AAM aircraft designs and their marketability. A key conclusion drawn from this review is that one-passenger autonomous air-taxis will accommodate over 80 percent of all travel trips and are likely to dominate this future personal airborne mobility market. Consequently, Dr. Moller and his team have decided to concentrate on the one passenger Skycar® 100. MI's team preferred its hybrid version; however, without knowing the FAA's position regarding the use of batteries as an energy source, MI will start the FAA approval process for the engine powered Skycar® 100. Approval will be sought under a variation of the FAA's special category for recreational aircraft (S-LSA or Part 103).





XM-2 **XM-3**



Neuera 200 **M400 Skycar®**

Skycar® 100X

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