eVTOL and Flying Car Technology Simplified with a Tire-Propeller Hybrid

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Abstract

New forms of air transportation are being explored as congestion on today's roads steadily increases. Of the new forms of air transportation being explored, electric vertical takeoff and landing (eVTOL) aircraft could be the future of sustainable transportation to reduce greenhouse gas emissions. Even though they are promising, many existing eVTOL architectures will likely struggle to be widely adopted due to the need for appropriate vertiports. This paper discusses flying cars and Flying Car Transportation Systems (FCTS), vehicles with driving and flying capability, as a subset of eVTOLs to let one efficiently travel from home, vertiport, and destination and vice versa without interruption. In particular, the novelty of a tire-propeller hybrid (TPH) is considered as a simplified propulsion system for both driving and flying that enables the widespread adoption of eVTOLs. A concept for one is proposed, and a simple feasibility analysis based on momentum theory is conducted.

Introduction

The concept of an Electric Vertical Take-off and Landing (eVTOL) aircraft continues to be of interest for discussion in the 21st century. As the discussion for eVTOL aircraft continues, flying cars (vehicles with both driving and flying capability) are also being explored. Both forms of transportation will hopefully relieve modern transportation problems.

A. Current Transportation Problems

More problems relating to transportation persist as the world's population increases. The following elucidates a few of these issues.

1) Traffic Congestion

Traffic congestion is a transportation state characterized by longer trip times and slower speeds. The INRIX Global Traffic Scorecard for 2022 stated that 58% of urban areas analyzed experienced increased traffic delays over last year, with cities like London and Boston experiencing 156 and 134 hours of delay per driver [1]. Vehicles like eVTOLs and flying cars are being introduced to offer air travel as an alternative to ground-based transport. Thus, these vehicles will utilize the less crowded near-ground spaces (NGS) to relieve congestion [2].

2) Emissions

Vehicles that combust fuel release greenhouse gasses (GHGs) that contribute to climate change. Vehicle emissions are a main cause of GHG emissions. Specifically in the United States, vehicle emissions account for 29% of total GHG emissions [3]. Therefore, more electric-based vehicles like eVTOLs are being explored to counteract GHG emissions.

3) Outdated Infrastructure and Technology

Many transportation systems, specifically in urban environments, still rely on outdated technology. As congestion and emissions continue to increase, new inventions using renewable energy are being explored. Andrew R. Goetz, a Professor in the Department of Geography and the Environment at the University of Denver, states that the “magic bullet” approach for revolutionizing transportation relies on the promise of new technology [3]. The new technology considered here are eVTOLs.

B. Advanced Air Mobility (AAM)

The AAM concept focuses on developing air transportation systems that can transport people or cargo between local, regional, intraregional, and urban areas. AAM will be facilitated by new forms of aircraft such as eVTOLs and flying cars. Different subsets of AAM include Urban Air Mobility (UAM) and Regional Air Mobility (RAM).

UAM focuses on providing sustainable transportation of intra-urban distances below 150 km with an emphasis on eVTOL transportation [4]. On the other hand, RAM will support longer trips between 150-800 km and will not need new landing sites in or around urban cores [4]. As it stands, RAM will likely gain momentum sooner than UAM. Certain RAM aircraft will be hybrid or hydrogen-fueled aircraft, allowing them to use existing ground infrastructure, unlike UAM aircraft [4].

The AAM industry is growing as the AAM market in the US is expected to reach $115 billion annually by 2035 with 280,000 high-paying jobs [5]. Specifically, eVTOL aircraft and the industry have gained popularity. Around 500 eVTOL concepts, prototypes, and production vehicles have been introduced since the fourth quarter of 2022 [27]. This increased interest in eVTOLs may allow them to hit the market and be ready for commercial use as soon as 2025.

eVTOL Technology, Design, and Challenges

eVTOL aircraft are vehicles that can take off vertically like a helicopter, thus limiting the infrastructure needed for takeoff. Unlike helicopters, eVTOLs are powered by electric motors instead of conventional combustion engines and use distributed electric propulsion systems. Researchers expect that a fully loaded eVTOL can have lower emissions than electric cars [6]. Different eVTOL configurations and flight mechanisms have been introduced that incorporate these distributed electric propulsion systems to achieve vertical lift for takeoff and landing as well as forward flight [6]. Below is a classification of different eVTOL configurations and flight mechanisms.

A. Powered Lift

Powered lift aircraft have a fixed wing for horizontal flight, but have vertical take-off and landing (VTOL) components. There are two major subcategories of powered lift aircraft.

1) Lift and Cruise

Aircraft in this category have independent thrusters for lift and cruise with the lift rotors usually lying vertically on a fixed wing. Due to the existence of lifting surfaces (i.e. wings), these aircraft are usually cruise efficient [6]. Independent propulsion units for lift and cruise reduces the cost/complexity; however, since not all units are active during different phases of the flight, the inactive units increase drag [7].

2) Vectored Thrust

This category consists of aircraft with the same propulsion system for both lift and cruise by rotating the propulsion units [6]. These aircraft tend to be more mechanically complex than other configurations, increasing the weight of the aircraft at the expense of the payload capacity. The variations are listed below.

Tilt-rotor aircraft are variations of the vectored thrust class with good speed and range, usually above 100 km [6]. In these aircraft, the rotors are mounted on the rotating shaft of the fixed wings. They tend to provide more control flexibility as the rotors stay parallel to the round during hover and rotate vertically when the aircraft gains speed [6]. One famous example of a tilt-rotor configuration is the V-22 Osprey; however, the Osprey is gas-powered.

Tilt-wing aircraft are characterized by the wings and rotors mounted on it rotating as a single system. The wing rotates up for vertical take-off and stays horizontal and fixed during forward flight. Compared to tilt-rotors, tilt-wing aircraft are more hover efficient due to wing rotation but have a single point of failure due to the integrated wing/rotor system [6].

3) Combined Thrust

eVTOLs under the combined thrust category have propulsion units that can provide vertical lift and rotate for forward thrust while other units are fixed and only provide vertical lift [7]. Unlike lift and cruise aircraft, the drag is mitigated because all propulsion units are used during vertical lift, but they are more costly and complex [7].

B. Wingless

As the name suggests, wingless eVTOLs do not have wings and rely on the rotors for lift and forward flight.

2) Multicopter

Multicopters possess many rotors that only provide vertical lift. Thus, these aircraft are controlled by differing speeds of the rotor units. Unlike the powered lift class, multicopters fly at a lower cruise speed and altitude due to the absence of fixed wings [7], making them ideal for short-range flights to avoid traffic jams [8]. In addition, they are not as efficient in cruise due to the absence of wings, but all their rotors can generate thrust to offset gravity. They do not require heavy infrastructure to tilt their rotors unlike tilt-rotors; consequently, the body of the aircraft tilts more during flight, potentially making passengers less comfortable.

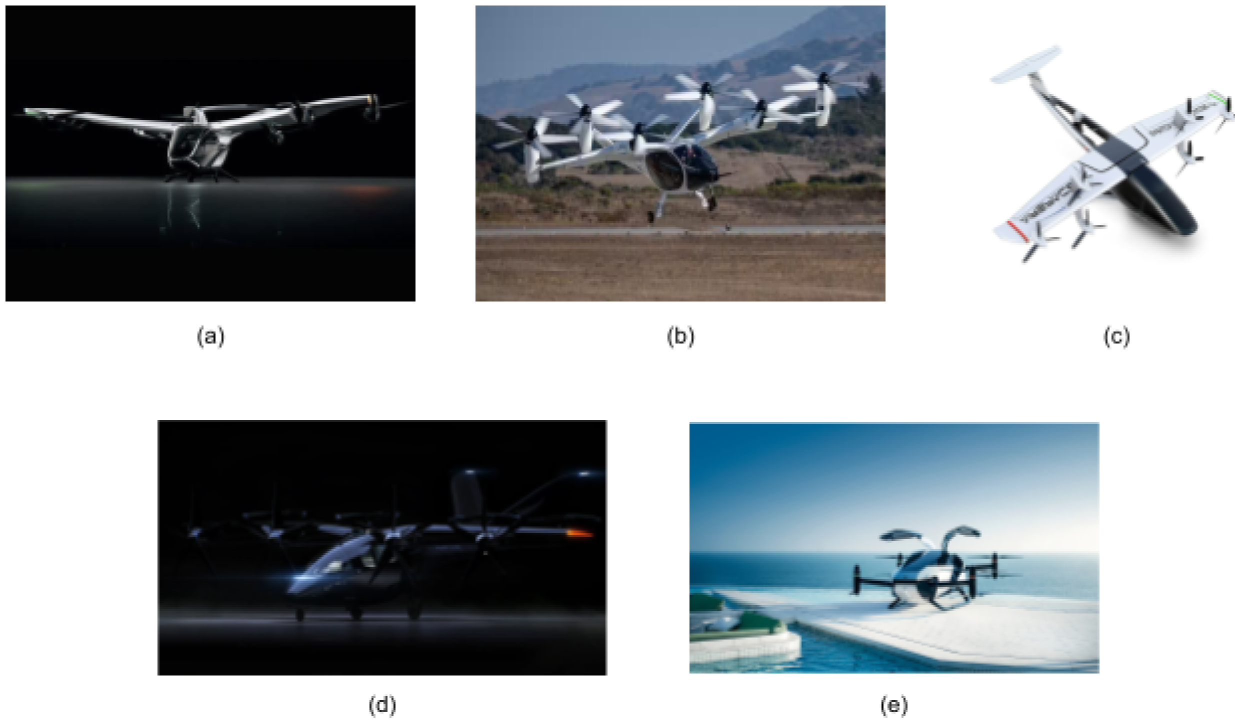


Fig. 1. One eVTOL for each category listed below. (a) CityAirbus NextGen: Lift and cruise [28]. (b) Joby S4: Tilt-rotor [29]. (c) MOBi-One: Tilt-wing [30]. (d) Vertical Aerospace VX-4: Combined thrust [31]. (e) XPeng X2: Multicopter [32].

TABLE 1. Specifications of current eVTOLs [27].

Vehicle	Configuration	MTOW (kg)	Range (km)	Cruise Speed (km/h)	Total Seating Capacity
Terrafugia TF-2a	Lift and cruise	1,200	100	180	3
ALIA-250		2,721	500	270	5
CityAirbus NextGen		2,200	80	120	4
Archer Aviation Midnight	Tilt-rotor	3,175	80	241	5
Joby S4		2,177	241	322	5
ASX MOBi-One	Tilt-wing	-	103	240	4
Airbus Vahana		815	60	200	1

Vertical Aerospace VX-4	Combined thrust	-	161	241	5
Volocopter 2x	Multicopter	450	27	102	2
XPeng X2		840	54	130*	2

* This is the maximum speed instead of cruise speed.

C. Challenges of Existing eVTOLs

Although eVTOLs present many benefits for the future of transportation, there are challenges preventing the implementation of a full-scale eVTOL transportation system.

1) Technology Issues

Battery life and efficiency is a concern in full eVTOLs. Li-ion batteries are the staple in current energy systems; however, using li-ion batteries in electric aircraft is challenging due to its specific energy limitations. The highest specific energy of a Li-ion battery is over 700 Wh/kg compared to jet fuel's specific energy of 12,000 Wh/kg [9] [10]. New power sources are being explored to resolve this limitation, but until then, existing electric power supplies take up most of the payload capacities for eVTOLs.

The adoption of autonomous flight is also a challenge. Many eVTOLs mention automated flight as a way to eliminate the need of pilots and thus reduce the overall weight of the craft. However, true automated flight without a pilot is decades away, so the need for pilots will remain a problem at present [11].

2) Public Acceptance

Like other vehicles, the safety of eVTOLs must be assured for the industry to succeed. eVTOLs are introducing advanced and disruptive technology, so these must be made familiar and safe for the public eye [12].

Noise from the propellers is another issue of concern. Since eVTOLs will be traveling relatively close to the ground, the propellers must have a low noise emission so as not to disrupt public activity.

3) Infrastructure

The adoption of eVTOL or any AAM transportation system will require altering existing infrastructure and creating new ones for vertiports and charging ports. Not only that, but infrastructure will also be needed for traffic management and telecommunications [13].

Since eVTOLs take off and land vertically, runways are not needed. However, the takeoff and landing pads have to be appropriately sized to fit the variety of eVTOLs and spaced apart from each other [14]. For urban areas, finding suitable locations for vertiports may be difficult due to the lack of space. Possible locations for AAM ground infrastructure include on rooftops, inside highway-clover leaves, on top of ground-transport infrastructure, and on barges over water [13].

Spaces for charging ports is also a concern. Charging ports have to be strategically spaced apart from each other so the eVTOLs can safely finish their trips without running out of power [14].

Flying Cars and Transportation Systems

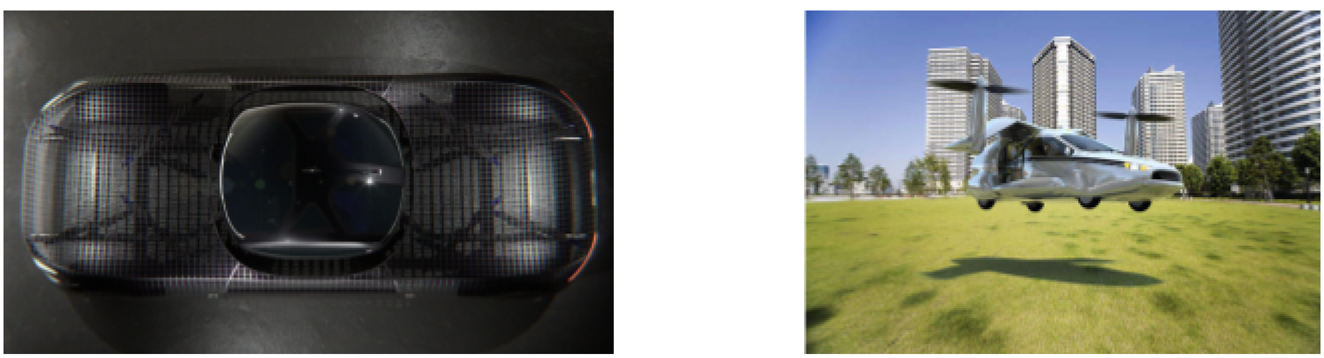
Flying cars continue to be a well-established abstract in society. These hybrid vehicles have driving capabilities like a car, but they also have flight capabilities usually through VTOL. The concept of a flying car is not new; it has been around for over a century with Glenn Curtis creating the first flying car known as Autoplane in 1917 [15]. Interest in flying cars, especially in the United States, is increasing as IT companies like Uber and Google have taken an interest in these vehicles [16].

A. Current State of Flying Cars

As there are no specific classifications for flying cars, a wide variety of technology demonstrators and concepts have been introduced.

Alef Aeronautics has received an experimental category special airworthiness certificate for their flying car, Armada Model Zero. This vehicle is fully electric with eVTOL capabilities, having a flight range of 110 miles and driving range of 200 miles [17]. The design is drastically different from a conventional car; the driver seat is in the middle surrounded by a mesh outer layer with eight propellers placed within the mesh [17].

Terrafugia proposed a concept for an autonomous flying car called the TF-X. This vehicle will have VTOL capability, using a 300 hp gas turbine engine with two 600 hp electric propeller pods [18]. The TF-X is a tilt-rotor in flight with a range over 800 km [19].



(a) (b)

Fig. 2. Current concepts for flying cars. (a) Alef Aeronautics' Armada Model Zero (multicopter with props placed within the car frame) [17]. (b) Terrafugia's TF-X (tilt-rotor with foldable wings) [19].

Flying cars may be the future of transportation, but there are challenges within their designs:

- Aerodynamic problems due to a combined system since a road vehicle has different issues than an aircraft [18];
- High power demand must be met for driving and flying capabilities, which requires the source of energy to be thoroughly thought out;
- High vehicle weight resulting from combining driving and flying systems;
- Incorporation of both driving and flying systems may result in unwieldy designs, making them hard to fit in existing infrastructure;

- Mechanically more complex, which raises the weight and price of these vehicles.

B. Flying Car Transportation Systems (FCTS)

FCTS describes flying car transportation systems to utilize the underused, near-ground spaces (NGS) of around 100 meters above ground level [20]. This system will utilize existing infrastructure such as public roads, but the flight capabilities will help relieve congestion on the roads and provide shorter commute times. Other benefits of FCTS are listed below:

- Less vehicle emissions as most flying cars will be fully electric or hybrid power source;
- Less infrastructure required because most flying cars are VTOL and will use existing infrastructure;
- More space on the roads for ground based transport;
- Can reach areas an aircraft with only flight capabilities would not be able to due to driving capabilities (eg. residential areas and neighborhoods).

Compared to other models of AAM transportation systems, FCTS offer advantages. For one, flying cars will better utilize the limited infrastructure and prevent the need for more. Less vertiports would be needed as the driving capability will allow travel to a vertiport and to the final destination from a vertiport. Flying cars also effectively combine two forms of travel, providing a passenger greater efficiency by traveling in one vehicle rather than multiple.

FCTS will face similar issues as other AAM transportation systems. First, public acceptance is a recurring issue because of the disruptive technology flying cars introduce. Also, the benefits of a combined system of travel over separate vehicles of ground and air transportation has to be made clear. Second, passenger safety is a concern because of the high altitude flying cars will cruise at. Not only that, FCTS imposes the danger of a flying car malfunctioning over an urban sprawl and jeopardizing the safety of those at ground level [20]. Lastly, noise suppression and the need for pilots will prevent the full implementation of FCTS for reasons mentioned in the eVTOL section.

Analysis of a Flying Car with a TPH

A tire-propeller hybrid (TPH) is any propulsion system that incorporates propeller and wheel functions under a combined system. Variations of the TPH include propellers concentrically placed inside wheel rims or structures that function as both a wheel and propeller like in Goodyear's AERO concept [22]. The wheels function as both a duct for a propeller and for the drive mode. The TPH concept will potentially allow for a more compact flying car and high functional integration between drive and flight modes [21].

Although this concept is relatively new, there have been recent attempts to incorporate a similar concept. One example is the Goodyear AERO concept introduced in 2019. It is a two-in-one tire that functions as both the wheel and propeller for the aircraft [22]. The design includes a non-pneumatic structure, magnetic propulsion, and optical sensing to monitor the tire's physical state [22]. Furthermore, Caltech's M4 drone achieves eight types of motion including drive and flight modes [23]. The drone has four wheels with a propeller placed concentrically in each, and to fly, the wheels are folded up and repurposed to rotors. The M4 is a small scale demonstrator that validates the TPH concept, but it remains unknown if this concept can scale up to a human-carrying aircraft.

(a)

(b)

Fig. 3. Concept and prototype that uses the TPH design. (a) Goodyear's AERO tire (two-in-one tire) [22]. (b) Caltech's M4 drone (propellers ducted inside tires) [23].

A. Proposed Idea

A flying car that includes the TPH concept and carries two people is proposed. For this design, a propeller will be placed concentrically within each wheel rim instead of a singular structure to prevent a single point of failure. The vehicle will be purely electric powered by Li-ion batteries to make it as environmentally friendly as possible. In addition, an electric motor and propeller will be placed concentrically within each wheel rim for individual-wheel-drive (IED) in drive and distributed electric propulsion (DEP) in flight. To transition between drive and flight mode, the wheel will be rotated until horizontal for VTOL. Some sort of actuated suspension and transmission will be used to facilitate the transition [21]. The vehicle will be used for short-haul flights for UAM, so a multicopter configuration is chosen to avoid the added mass and size of wings.

To simplify sizing calculations, the mass of the vehicle's frame is assumed to be 5% of a solid block's volume of a given material. Since many electric aircraft use a carbon fiber composite for the fuselage, the mass of the vehicle's frame is assessed in terms of carbon fiber's density of 0.029 kg/in^3.

TABLE 2. Parameters of a flying car with the TPH concept.

Parameter	Value	Reference
Frame length	4.8 m	Based off Xpeng's X2 flying car [24]
Frame width	2.0 m	[24]
Frame height	1.3 m	[24]
Number of rotors	4	-

Battery energy density	0.7 kWh/kg	Assuming highest energy density achieved of rechargeable Li-ion batteries [9]
MTOW	2350 kg	-
Empty weight	2200 kg	-
Frame mass	1124 kg	Assumed to be around 5% of solid block's volume of a certain material
Combined motor mass	196 kg	Based on Siemen SP200D direct drive motor [33]
Battery mass	880 kg	Assumed that around 40% of an electric aircraft's empty weight is the battery
Payload capacity	150 kg	Two passengers and cargo

Since flying cars need to be compact to fit within existing road infrastructure, the diameter of each TPH should be anywhere from 13-24 inches to fit within the range of typical road vehicles [25]. The next section is focused on estimating an individual rotor's diameter.

A. Methodology for Estimating TPH Diameter

Although the power and energy demand for an aircraft is different at various mission stages, this analysis will only consider the power at hover (P_{hover}) to approximate the power consumption during flight.

The battery capacity (E) of the vehicle is given in kilowatt-hours (kWh), which can be calculated through the equation:

$$E = m_{battery} E_D \quad (1)$$

where $m_{battery}$ is the battery mass in kg and E_D is the battery's energy density in kWh/kg. To solve for the P_{hover} per rotor for a given flight time, the equation below is used:

$$P_{hover} = \frac{E}{nt} \quad (2)$$

where n is the number of propellers and t is the flight time in hours (h).

Using momentum theory, the ideal power can be estimated through the equation [26]:

$$P = \frac{T^{\frac{3}{2}}}{\sqrt{2\rho A}} \quad (3)$$

where P is the ideal power measured in Watts, T is the thrust in Newtons, ρ the air density (1.225 kg/m^3), and A the area of the rotor disc in meters squared. The thrust should be equal to the weight of the aircraft at hover assuming there is no acceleration in any direction. Thus, the thrust per rotor (T_{rotor}) is equal to

$$T_{rotor} = \frac{1}{n} m_{MTOW} g \quad (4)$$

where g is the acceleration due to gravity (9.81 m/s^2). Since the P_{hover} per rotor is known, the ideal power (P) will be substituted with P_{hover}. T_{rotor} can be substituted into the ideal power equation to solve for P_{hover} per rotor, and A is equal to πr^2 where r is the radius of the rotor in meters. Substituting these values and solving for r results in

$$r = \frac{m^{\frac{3}{2}} g^{\frac{3}{2}}}{n^{\frac{3}{2}} P_{hover} \sqrt{2\rho\pi}} \quad (5)$$

The diameter (d) can then be solved by doubling the radius (r) found in the equation above.

B. Results

Using the methodology listed above, a basic Java program (listed in Appendix A) was written to test multiple flying car sizings. From this process, a diameter of 0.72 m (28.3 in) is deduced using the specifications in Table 2 and assuming a flight time (t) of 0.35 hours (21 minutes).

Although the diameter exceeds the typical wheel diameter of 13-24 inches in road vehicles, the wheel rims can potentially act as a duct for the propellers. This allows for a higher lift generation and a smaller rotor diameter [21]. The wheel rim will then need to function as an effective duct that decreases the rotor diameter without decreasing the thrust.

The same process is used to estimate the TPH diameter of a flying car with eight propellers, resulting in an increase of 196 kg in MTOW. The other specifications listed in part A are the same. It is deduced that a flight time of 0.43 hours (26 minutes) yields a diameter of 0.7 m (27.6). Thus, there is a direct relationship between number of propellers, flight time, and MTOW.

Conclusion

This paper offers an overview of current eVTOL and flying car technology. These two types of vehicles could potentially be the future of transportation, reducing travel times and relieving congestion on today's roads. Even though they are promising, there are limitations regarding infrastructure and technology. New infrastructure for vertiports and charging stations are needed, and existing infrastructure like aerodromes can be modified to accommodate eVTOLs and flying cars. Batteries are also a problem as Li-ion batteries have limited specific energies that make fully-electric VTOL vehicles less efficient.

Furthermore, a simplified analysis of flying cars with the TPH concept is presented. Small scale demonstrators like the M4 drones use this concept, but there is currently no fully-scaled technology demonstrator that implements the TPH design. The goal of the TPH is to effectively integrate both drive and flight systems, reduce mass and size, and design a flying car that looks similar to typical road vehicles. From the results in the section above, it is possible to reduce the wheel/rotor diameter to that of a typical road vehicle, but it greatly reduces the flight time. Therefore, this type of flying car will be most effective flying over areas of congestion or short urban flights of twenty minutes or less. The limited passenger capacity may hinder the commercial use of flying cars with the TPH concept and other variations, so these vehicles will initially be for private use and eventually transition to commercial use. More rotors can be added to increase the flight time at the expense of an increase in MTOW and overall size, potentially making flying cars more unwieldy on roads. These additional rotors, which are not TPHs, can be placed underneath the car's frame to provide only vertical thrust similar to Alef Aeronautics Armada Model Zero. Different types of power supplies (hybrid and hydrogen fuel) should also be explored since a fully-electric approach is limited despite the advancements of Li-ion batteries.

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Appendix A

Java Code for Basic Flying Car Specifications

```
/**
This program is for basic flying car sizing. It is based on a simplification that the
vehicle's body
is around 5% of the weight of solid block made out of a material. It calculates the
radius of
each rotor based on momentum theory given the parameters entered by the user in main.
@author Justin Doan
*/
public class FlyingCarSpecs{
   public static void main(String[] args){
       flyingCar example = new flyingCar(188.6, 76.8, 53.5, 0.029, 880, 0.7, 150, 0.35,
4);
       example.printSpecs();
   }
}
/**
This class represents a flying car.
*/
class flyingCar{
   private double length;
   private double width;
   private double height;
   private double density;
   private double batteryWeight;
   private double batteryDensity;
   private double timeInHours;
```

```
    private double cargoWeight;

    private int props;


    /**

     Constructs and initializes a flying car with the parameters listed below.

     @param length length of the vehicle frame in meters

     @param width width of the vehicle frame in meters

     @param height height of the vehicle frame in meters

     @param density density of the material that makes up the vehicle body in kg/m^3

     @param batteryWeight weight of the battery supply in kg

     @param batteryDensity density of the battery supply in kW/h*kg

     @param cargoWeight max cargo weight (passengers and baggage) in kg

     @param timeInHours max desired flight time of the vehicle

     @param props number of propellers/rotors

     */

    public flyingCar(double length, double width, double height, double density, double
batteryWeight,

                    double batteryDensity, double cargoWeight, double timeInHours, int
props){

        this.length = length;

        this.width = width;

        this.height = height;

        this.density = density;

        this.batteryWeight = batteryWeight;

        this.batteryDensity = batteryDensity;

        this.cargoWeight = cargoWeight;

        this.timeInHours = timeInHours;

        this.props = props;
```

```
    }
    /**
     Prints relevant specifications for the flying car.
     */
    public void printSpecs(){
        double volume = length*width*height;
        double massInKg = volume*density;
        double frameMass = massInKg*0.05;
        double totalMassInKg = frameMass + batteryWeight + cargoWeight + (49*props);
        double thrust = totalMassInKg*9.81;
        double thrustPerMotor = thrust/props;
        double batteryCapacity = batteryDensity*batteryWeight;
        double pHoverPerMotor = ((batteryCapacity / timeInHours) / props)*1000;
        double radOfRotor = (Math.pow(totalMassInKg, 1.5) * Math.pow(9.81, 1.5)) /
                (Math.pow(props, 1.5) * pHoverPerMotor * Math.pow(2*1.225*Math.PI,
0.5));
        String details = String.format("Block volume: %.2f", volume) +
                String.format(" m^3 | Frame mass = %.2f" ,frameMass) +
                String.format(" kg | Total mass = %.2f" ,totalMassInKg) +
                String.format(" kg \n\nThrust = %.2f" ,thrust) +
                String.format( " N | " + "Thrust per motor = %.2f" ,thrustPerMotor) +
                " N | Battery capacity = " + batteryCapacity +
                String.format(" kWh \n\npHover per prop = %.2f" ,pHoverPerMotor) +
                String.format(" W | Radius of rotor = %.2f", radOfRotor) + " m";
        System.out.println(details);
    }
}
```