Design Perspectives on Delivery Drones

Jia Xu

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Published by the RAND Corporation, Santa Monica, Calif.

Preface

Delivery drones may become widespread over the next five to ten years, particularly for what is known as the "last-mile" logistics of small, light items. Companies such as Amazon, Google, the United Parcel Service (UPS), DHL, and Alibaba have been running high-profile experiments testing drone delivery systems, and the development of such systems reached a milestone when the first commercial drone delivery approved by the Federal Aviation Administration took place on July 17, 2015. In the future, drones could augment, or in some situations even replace, truck fleets and could have important implications for energy consumption, public safety, personal privacy, air pollution, city noise, air traffic management, road congestion, urban planning, and goods- and service-consumption patterns in urban areas.

To support developing issues regarding delivery drones, the RAND Corporation launched an exploratory study that brings together RAND's expertise in unmanned aerial vehicle (UAV) operations, transportation research, systems analysis, and behavioral analysis and applies it to this emerging and underexplored research area.

The larger project explores the city-scale impacts of delivery drone operations on the following areas: energy consumption, infrastructure requirements, aerial congestion, privacy, and noise. The other forthcoming RAND publications include the following:

- What's the Buzz on Delivery Drones? (Welser and Xu, 2016)
- What's the Buzz? The City-Scale Impacts of Drone Delivery (Lohn, 2017)
- The Energy Implications of Drones for Package Delivery: A Geographic Information System Comparison (Gulden, 2017)
- Small Unmanned Aerial System Certification and Traffic Management Systems (Kuhn, forthcoming)
- International Commercial Drone Regulation and Drone Delivery Services (Jones, forthcoming).

In this report, we explore the design aspects of delivery drones, including projects of likely current and future system performance.

Questions or comments about this report should be sent to the project leaders, William Welser (William_Welser@rand.org) and Jia Xu (Jia_Xu@rand.org).

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Funding for this venture is provided by the generous contributions of the RAND Justice, Infrastructure, and Environment Advisory Board and other donors to that division. Collectively, their contributions reflect pooled grants from a range of sources, including corporations, trade and professional associations, individuals, government agencies, and private foundations.

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Summary

As the demand for commercial deliveries increases within cities, companies face a fundamental limitation in surface road capacity. Drone delivery aims to overcome that limitation by exploiting the vertical dimension above city streets. This report explores the vehicle design aspects of the delivery drone problem, including flight efficiency, energy consumption, noise, and safety, which are central to the viability of delivery drones. Importantly, key design constraints and expected performance levels also speak to the potential scalability of the concept.

A brief analysis of the requirements shows that a 10- to 15-mile delivery radius is likely sufficient to cover most U.S. urban areas. A vertical takeoff and landing (VTOL) delivery drone can ease operations at the terminal area at a cost to flight efficiency. The limited delivery range and payload requirements, coupled with the power efficiency of electric motors at small scales, make VTOL viable. The relatively scale-free nature of electric propulsion further reduces the cost of mounting separate and optimized cruise and hover motors. This helps to bridge the long-standing gap between good hover and cruise performance in VTOL aircraft (at least for small, short-range applications).

To better understand the short-term technical viability and future prospects of delivery drones, we developed and tested a simple delivery drone performance model. The model takes in a host of vehicle and mission parameters and assumptions, chief among which are the aerodynamic, structural, and propulsive efficiencies and the battery energy density. The model is high level, and the parameters are based on analogous systems. We do not attempt to create detailed aerodynamic and structural designs to produce detailed vehicle configurations. Rather, the vehicles are designed against notional mission requirements framed in terms of payload, range, and hover and climb requirements.

The primary outputs of interest are the energy consumptions and masses of converged delivery drones, which have been properly sized (including cruise, hover, and reserve flight segments) to carry all the payload and onboard systems. In technical terms, we use fixed-point iterations to converge the empty weight of the drone designs.

Using the model, we examine both a baseline design and an advanced design. We find that, for the baseline design, the Google Project Wing– and Amazon Prime Air–type delivery drones represent the limit of what is possible when assuming a simple, moderately efficient hybrid multicopter configuration and today's battery-specific energy density. For this class of drones, we estimate the energy to deliver a 5-lb payload out to a radius of 10 miles to be about 1.5 kilowatt hours (kWh).

Looking forward, we find that an advanced design enables more gains through aerodynamic refinements and improved batteries. The combination of a higher lift-to-drag ratio (scaled from today's VTOL tilt-rotor designs), denser batteries, improved structural efficiencies, and blended

aerodynamic and propulsive control could dramatically reduce energy consumption, leading to five- to sevenfold improvements in flight efficiency. Improved flight efficiency could support multi-stop delivery drones, which could be more efficient, but it also requires sufficiently dense delivery demands.

Acknowledgments

I would like to thank Ilan Kroo and Mykel Kochenderfer at Stanford University, Rick Gaeta at Oklahoma State University, and Parimal Kopardekar at NASA for their support and insights during this project. Will Hetzler at Zipline and Paola Santana at Matternet also provided valuable input on drone operations. I also thank Juan Alonso at Stanford University and Richard Mason at the RAND Corporation for their thoughtful reviews of the draft document. Finally, I am grateful to my co–principal investigator, Bill Welser, for bringing together our diverse team of RAND researchers for this timely project.

Abbreviations

BSFC	brake shaft–specific fuel consumption
CTOL	conventional takeoff and landing
FAA	Federal Aviation Administration
IC	internal combustion
L/D	lift-to-drag ratio
NASA	National Aeronautics and Space Administration
RPM	revolutions per minute
sUAS	small unmanned aerial system
T/W	thrust-to-weight ratio
UAV	unmanned aerial vehicle
VTOL	vertical takeoff and landing

Chapter One. Introduction

Background

Against the backdrop of rapid commercialization of unmanned aerial vehicles (UAVs), there is growing interest in using drones to perform last-mile parcel delivery—defined as the last leg of the delivery process to the consumer's home or business. As the demand for commercial deliveries increases within cities, companies face a fundamental limitation in terms of surface road capacity. By exploiting the vertical dimension above city streets, drone delivery aims to overcome that limitation.

Companies such as Amazon, Google, and DHL have all launched substantial technical and, in some cases, coordinated public policy programs to bring drone delivery to fruition. A host of smaller start-ups are also working on delivery drones for developed and emerging markets (D'Andrea, 2014). In a related development, start-ups and established aerospace players (e.g., Airbus) alike are pursuing larger aerial on-demand mobility platforms—flying taxis designed to autonomously transport individual passengers from point to point (Vance and Stone, 2016). Not only do the larger passenger-carrying concepts share many of the same airframe, propulsion, and autonomy technologies as the smaller delivery drones, but they may be productively used to deliver larger, bulkier cargoes.

Some of the possible business and competitive motivations for using drone delivery include reducing the cost of delivery; differentiating brands; and, in the case of online retailers, reducing customer foot traffic and impulsive purchases in competing brick-and-mortar stores. Moreover, while delivering packages, drones can also be used to establish ad hoc communication networks or collect geospatial and business intelligence data.

Beyond the business imperatives, key technological developments are also aligning to enable drone logistics systems. The last decade has witnessed the proliferation of smartphones and electric cars, as well as the emergence of autonomous ground vehicles. These developments have contributed to the technical and operational viability of drone-based logistics in two ways:

1. The combination of affordable, high–energy density lithium ion batteries and high–power density electric motors opens up the possibility for efficient vertical takeoff and landing (VTOL) aircraft at small scales.
2. Reliable, miniaturized, and increasingly autonomous integrated sensor, flight control, sense-and-avoid (including computer vision), and navigation systems reduce the cost and operating risks associated with drone operations.

Objectives and Approach

This report explores the vehicle design aspect of the delivery drone problem, including flight efficiency, energy consumption, noise, and safety, which are central to the viability of delivery drones. Importantly, such designs also speak to the potential scalability of the concept. As noted in the preface, the delivery drone study has produced a series of complementary reports that together rely on three key approaches: a literature review, expert discussions, and modeling and simulation. In this work, we developed and exercised a simple delivery drone performance model to better understand the short-term technical viability and future of delivery drone prospects. The model is discussed in more detail in Chapter Four.

Organization of This Report

In the remainder of this report, we look at the requirements that drive drone delivery (in Chapter Two), vehicle configuration (in Chapter Three), and performance model and outlook (in Chapter Four), before offering some conclusions in Chapter Five. An appendix provides the assumptions underlying the modeling discussed in the main report.

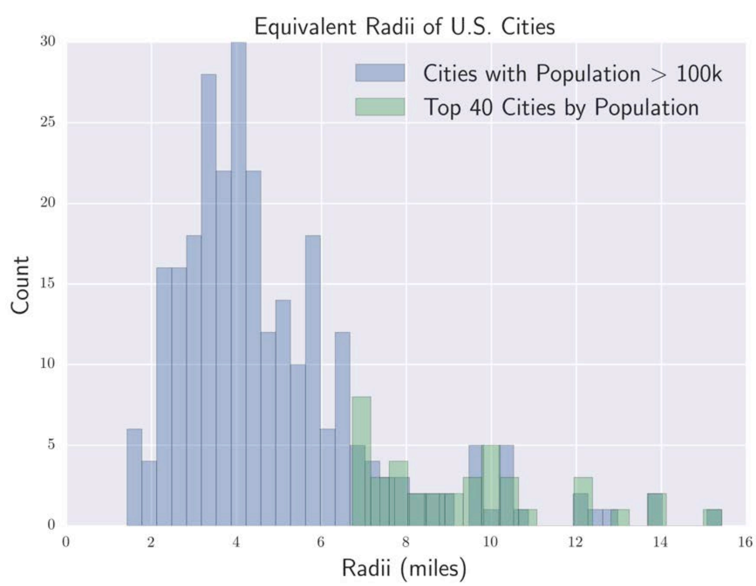
Chapter Two. Requirements That Drive Drone Delivery

In this chapter, we consider the flight performance, configuration, power and propulsion, and noise abatement requirements that drive delivery drone design.

Flight Performance

Delivery drones are envisioned to execute point-to-point delivery of small parcels. As illustrations, Amazon and Matternet aim for initial operating radii on the order of 10–15 miles (or 16–24 km) (Amazon, undated). A first-order question is whether this range is sufficient to ensure that companies can deliver parcels in a city. For context, the average physical area of the 40 most-populous U.S. cities is 290 square miles (United States Census Bureau, undated). If we idealize the footprints of the cities as circles, then the average radius comes to just 9.6 miles. If we go beyond the 40 most-populous cities and further consider all U.S. cities with more than 100,000 people, then the average radius drops to just 5.4 miles. Figure 2.1 shows that the radii of the vast majority of U.S. cities is in the 2–6-mile range. These results suggest that most cities can be covered by just a few drone fulfillment centers (located either in the urban centers or peripheries).

Figure 2.1. Distribution of Equivalent Radii of U.S. Cities If We Idealize Their Areas as Circles



SOURCE: United States Census Bureau, undated.

When we go outside urban areas, distances grow and densities fall, which hurts the operating economics of short-legged delivery drones. But as we shall see, with improved flight efficiency, delivery drones could also operate effectively in suburban and rural environments. We explore both single- and multi-stop delivery solutions in subsequent sections.

Configuration

Delivery drones must safely navigate the delivery area to drop off the package, and, ideally, they would do this autonomously. Existing solutions have tackled this requirement in one of two ways: (1) a VTOL vehicle that can hover over the delivery area and either drop off the package or land with it or (2) a fixed-wing, non-VTOL vehicle that can drop off a parachute-decelerated package at low altitude without having to land.

Given this, a first-order question is whether VTOL capability is needed for drone delivery. A VTOL drone does not need ground infrastructure, such as runways, and its ability to hover and maneuver in tighter airspaces is useful for getting the package into dense terminal delivery areas. By contrast, a fixed-wing, conventional takeoff and landing (CTOL) aircraft does not need to balance conflicting cruise and hover requirements and can thus operate more efficiently over longer ranges.

As shown in Figure 2.2, Zipline uses a fixed-wing drone to deliver medical supplies to low-density rural destinations. In this case, the drone launches from a catapult and flies to its destination, descends to drop a parachute-decelerated package, and is recovered either on the ground or in the air using what appears to be an arresting hook. The omission of VTOL capabilities allows the Zipline drone to be optimized for cruise, achieving a quoted mission radius of 55 km.

Figure 2.2. Zipline's Fixed-Wing Medical Delivery Drone

SOURCE: Zipline promotional image.

While efficient in cruise, CTOL drones likely need additional ground infrastructure and crews for launch and recovery—something that would incur an additional logistic burden and cost, particularly at scale. Additionally, ensuring that the parachuted packages reach their destination presents its own challenges. Dropping off an unguided parachute package at a low altitude is not feasible in vertically dense, urban landscapes. Guided-parachute packages released at higher altitudes and away from obstructions is one possible solution. Indeed, large, autonomous guided parachutes are used in the military to support forward logistics (Jorgensen and Hickey, 2005). However, an unpowered guided parachute suffers from low control authority and maneuverability and would have a hard time navigating around obstacles in built-up areas. The parachute and guidance package would also have to be inexpensive or recycled after each use. So, while the CTOL configuration is interesting for long-range, high-capacity applications in rural environments, it faces infrastructure and operational challenges in urban environments. For these reasons, we will focus on VTOL configurations in subsequent sections.

Power and Propulsion

For small-scale delivery drones that are flying short distances, electric power offers a number of advantages. An electric motor can be made reliable because it has only one moving part. In addition, electricity is cheap. At an average of ten cents per kilowatt hour (kWh), the energy cost of an electric road vehicle is only one-quarter of that of a comparable gasoline-powered vehicle in the United States. Yet despite improvements in battery capacity, orders of magnitude still separate the energy density of production lithium ion batteries (optimistically at 260 Wh/kg for battery cells only) and gasoline (11,944 Wh/kg).

The impact of reduced energy density is less severe for short-range aircraft, which do not have to carry the batteries as far to complete the missions. Also, the disparity in energy density is also partially compensated for by the substantially greater efficiency of the electric power system, particularly at a small scale: Small electric motors can be as much as nine times as efficient as comparable internal combustion (IC) engines (Menon and Cadou, 2009). Furthermore, the power density of the motor does not suffer at low output levels (Moore, 2012). At delivery drone scales, electric motors have an eight-to-one advantage in specific power versus small IC engines (Menon and Cadou, 2009). The comparatively scale-free nature of electric power translates into weight, volume, and drag savings for small vehicles.

Batteries do take time to charge, which places a bound on the utilization rate of the drones. However, the proliferation and technical maturation of rapid, multiphase charges for road vehicles means that charging is unlikely to be a limiting constraint, particularly given the low energy capacities of small drones that are flying short distances. Hot-swapping batteries is another way to decrease turnaround time and can allow the battery capacity (and, hence, the battery mass) to be tailored for individual missions.

Noise Abatement

Noise abatement is another potential design requirement. In the United States, the Federal Aviation Administration (FAA) has historically set aircraft noise regulations (although states and municipalities also play a role in shaping community noise standards). The FAA recently published its Part 107 rules to regulate small unmanned aerial system (sUAS) operations (including small commercial delivery systems). Part 107 mentions noise as a potential issue but also concludes that "the FAA lacks sufficient evidence at this time to justify imposing operating noise limits on . . . sUAS[s]. The only operating noise rules in the United States apply to turbojet aircraft and supersonic operations" (FAA, 2016). More research and experimentation are needed to establish the parameters for noise control and abatement.

Part 107 does indirectly limit noise by constraining all sUASs to weigh less than 55 lb. Other things equal, smaller aircraft will be less noisy than bigger ones. Part 107 also stipulates, very preliminarily, that small commercial drones cannot fly over people (except those who are operating the drones). This requirement, depending on its precise interpretation, may cut down on the effective noise impact. However, such strict overflight restrictions could also effectively curtail the prospect of drone delivery in dense urban environments. However, it should be noted that the restriction in the initial Part 107 formulation will likely evolve in the near future as the FAA works on requirements to expand small UAV operations to include beyond-visual-line-of-sight missions.

Aircraft noise is typically dominated by propulsion. In small delivery drones, electric propulsion can eliminate the noise sources associated with IC engines. However, the distinctive high-pitched noise from motor rotation may have to be managed. Rotor noise dominates other sources of noise (e.g., the engine and airframe) in most propeller-driven aircraft. Many rotor-design parameters affect noise: tip speed, thickness, blade count, sweep, tip shape, and blade twist. Of these, the rotor tip speed has perhaps the greatest impact: Maintaining a moderate subsonic tip speed is essential for controlling noise. As a thought exercise to determine the likely magnitude of noise from a delivery drone, we considered the heaviest possible drone allowed under sUAS rules (i.e., 55 lb). We assumed that it can be designed with a light helicopter-like disk loading of 4 lb per square foot. *Disk loading* is the ratio of weight to total rotor disk area. If we further assume that the drone is powered in hover mode with four rotors, each spinning at 3,000 revolutions per minute (RPM), then the rotor tip speed will be 330 ft per second, or Mach 0.3 at sea level. This is substantially lower than the near-sonic tip speed of typical helicopters at 700–800 ft per second, which operate (with significant noise) in the same altitude bands as delivery drones. The low tip speed in relation to existing platforms suggests that the noise of delivery drones can likely be controlled.

Distributed electric propulsion offers further potential for noise improvements. The ability to turn off rotors in different phases of flight and to optimize different rotors for hover and cruise can help a drone achieve optimal disk loading and flight efficiency across the flight envelope.

Improved rotor efficiency, in turn, cuts down emitted noise. Furthermore, distributed propulsion can also enable active noise abatement and cancellation technologies. NASA's GL-10 UAV demonstrator spins its ten rotors at slightly different speeds to distribute sound energy more evenly across different harmonics to minimize perceived noise. The GL-10 is claimed to be inaudible at an altitude of 30 m (Fredericks, Moore, and Busan, 2013).

With the potential for low tip speeds, synergies from distributed electric propulsion, and a large number of possible design degrees of freedom, the sUAS noise problem may be manageable, particularly in cruise at altitude. As another study in this RAND research series on delivery drones has highlighted, even at a modest cruise altitude of 100 m, the UAV noise source produces sound in the 50-dB region, which is considerably lower than the ambient noise threshold in most urban areas (Lohn, 2017). The focus of noise control should, therefore, be in takeoff if fulfillment centers are located in populated areas, and in landing, if the UAV has to land or hover at low altitude with power to deliver cargo. More research on this topic might be needed, since propeller noise is arguably an underresearched subject. This is not surprising, given the dominance of jet-powered aircraft in commercial aviation. And while noise abatement for helicopters and propeller-powered regional and general aviation aircraft have undoubtedly motivated advances in rotor aeroacoustics, these results have to be adopted and extended for small-scale applications, such as delivery drones. Analysis of drone delivery noise impacts would also have to take into consideration the potentially larger number of vehicles operating at any given time and changes in airspace access patterns to enable delivery (e.g., landing in neighborhoods to deliver payloads). Both factors may change the degree of human exposure to drone noise. Thus, there is both potential need and room for significant improvements.

Chapter Three. Vehicle Configuration

In this chapter, we discuss potential delivery drone vehicle configurations and design characteristics, as well as how electric delivery drones might differ from existing helicopters. Many delivery drone designs are either instantiations or derivatives of the popular electric multicopter configuration—the effective standard for today's small, commercial UAVs. The multicopter is both powered and controlled by an offset array of rotors, which are typically arranged in counterrotating pairs for efficiency. While multicopters can be and have been built with IC engines, small multicopters benefit greatly from the reliability and compactness of electric motors. The virtue of the multicopter is in its simplicity:

- Differential thrust replaces the mechanically complex combination of cyclic and collective pitch control needed to control conventional helicopters.
- High-bandwidth electronic RPM control can eliminate the need for variable pitch blades, albeit at a cost to vehicle dynamic response and control-power efficiency.
- The coaxial counter-rotating rotor arrangement simultaneously eliminates the need for counter-torque tail rotors and reduces swirl losses.
- In cruise, direct propulsive control also somewhat removes the need for aerodynamic control surfaces found on fixed-wing aircraft.

Multicopters, particularly those with more than four sets of rotors, achieve redundancy in the event of motor failure. By distributing power to a number of small rotors, individual moving rotors on the multicopter store less energy. Less energy means less damage to people or objects in the event of rotor impact (Hoffmann et al., 2007). Finally, the ability to physically fence in the small rotors—a feature that would be structurally infeasible for large helicopters rotors—further improves safety.

The multicopter's combination of mechanical simplicity and direct propulsive control greatly eases flight control system development, which is often one of the most complex parts of aircraft development programs. Simplicity and safety also eliminate barriers to entry and enable faster development cycles that prioritize experimentation and iteration over exhaustive analysis and modeling.

However, the basic multicopter's simplicity is achieved at a substantial cost to stability, flight control, and flight efficiency, especially for long-range cruise operations with substantial payloads. Because of the multicopter's propulsive control scheme, the motors will have to be oversized (beyond that which is necessary for hover) to maneuver at constant altitude. Rotor inertias also impose control delays: The bigger the rotor, the longer the delay. This means that multicopters have to be built with substantially oversized motors to decrease control delay. It is not uncommon for multicopters to be designed with thrust-to-weight ratios of 1.5–2.0. The result is that excess hover power sits unused over the cruise mission, while the additional weight of the oversized motors reduces flight efficiency.

Owing perhaps to its rapid, iterative development process, the aerodynamics of the multicopter is underresearched; interviews with subject-matter experts point to a lift-to-drag ratio (L/D)—a crucial determinant of aerodynamic performance—of about 1 for the basic multicopter. This means that the multicopter can glide horizontally at 1 m for every meter of energy potential lost in altitude.

For context, helicopters can achieve L/Ds of 4–5; moderately sized, fixed-wing UAVs can generally manage L/Ds of 10–15; and modern airliners can achieve an L/D of 20 in the much more demanding transonic flight regime. In a grossly simplified scenario where weight, payload, and propulsive efficiency are held constant between multicopters and fixed-wing configurations, the Breguet range equation, a first-order relationship describing aircraft flight efficiency, dictates that the L/D difference alone translates into a two- to threefold advantage in range for the fixed-wing platform:

$$R = v\frac{L}{D}I_{SP}\ln\left(\frac{W_i}{W_f}\right) \qquad \text{Eq. 3.1}$$

In practice, the terms in the Breguet equation are not independent. Hybrid configurations with aerodynamic lifting surfaces will need additional structure mass to support the lifting surfaces, thus reducing efficiency. Prop wash (or the impingement of propeller thrust) over wings can also reduce hover efficiency, but the basic trend still holds.

A substantial potential for improved cruise performance exists. Delivery drones should be well served by more-sophisticated fixed-wing VTOL or hybrid multicopter configurations that (1) optimally distribute aerodynamic loads between active and passive sources in cruise and (2) intelligently blend aerodynamic and direct propulsive control across the flight envelope. Indeed, Figure 3.1 shows that the latest vehicle designs revealed by Amazon, Google, and DHL all use aerodynamic surfaces to carry lift in cruise.

Figure 3.1. VTOL or Multicopter Vehicle Designs

Possible Amazon Prime Air Drone Design (Amazon)	DHL ParcelCopter 3.0 (DHL)	First Iteration Google Project Wing (Engadget)	Third Iteration Google Project Wing (Google)

SOURCES: Promotional images from Amazon, DHL, Google, and X Development.

This brings us to the “back to the future” character of the delivery drone design problem: The quest for an efficient fixed-wing VTOL configuration is as old as the aircraft itself. Many possible configurations and combinations have been tried in the last century. Indeed, all of the basic configurations shown in Figure 3.1 have been tried at one time or another. Yet the problem of the efficient, reliable, and affordable VTOL aircraft, some would argue, remained unsolved until now. The potentially game-changing technology that offers the prospect for efficient VTOL vehicles is electric propulsion.

The compact form factor and high–power density of modern brushless electric motors, the simplicity of electric power distribution (by wires rather than shafts or fuel lines), and improvements in battery energy density make a more distributed electric propulsion model possible. In simple terms, an electric aircraft can mount many small motors without dramatic weight penalties or mechanical complexities. In the VTOL context, aircraft can finally be efficiently equipped with dedicated cruise and hover motors. Large numbers of dedicated hover rotors reduce disk loading and improve hover efficiency, increase redundancy, and moderate the consequences of individual rotor failures. Thus, electric power and distributed propulsion can bridge the historical chasm between good hover and cruise performance in VTOL aircraft (at least for small, short-range applications).

The benefits of distributed electric propulsion also extend to more-complex and potentially more-efficient tilt-wing and tilt-rotor VTOL aircraft, such as the DHL configuration in Figure 3.1. Tilt-rotor aircraft such as the MV-22 and tilt-wing designs such as the DHL ParcelCopter 3.0 reorient their propulsors for hover and cruise. This variable geometry approach reduces the number of rotors needed. However, in the case of conventional gas-powered aircraft, the tilt-rotor and tilt-wing mechanisms incur significant penalties in mechanical complexity and weight. Most of these penalties come from the propulsion systems: Heavy engine assemblies have to be rotated between cruise and hover positions, fuel and power have to be reliably routed through wing or engine pivots, and widely separated engines have to be mechanically cross-shafted to evenly split power to cope with engine failure. Electrical power distribution conveniently sidesteps all of these challenges, while having lighter electric motors greatly simplifies pivot and actuator design.

Chapter Four. Performance Model and Outlook

To better understand the short-term technical viability and future prospects of delivery drones, we developed and exercised a simple delivery drone performance model. The model takes in a host of vehicle and mission parameters and assumptions, chief among which are the aerodynamic, structural, and propulsive efficiencies and the battery energy density. The model is high level, and the parameters are based on analogous systems. We did not attempt detailed aerodynamic and structural design in this model, and the key parameters and assumptions are detailed in the appendix. The vehicles were designed against notional mission requirements framed in terms of payload, range, and hover and climb requirements.

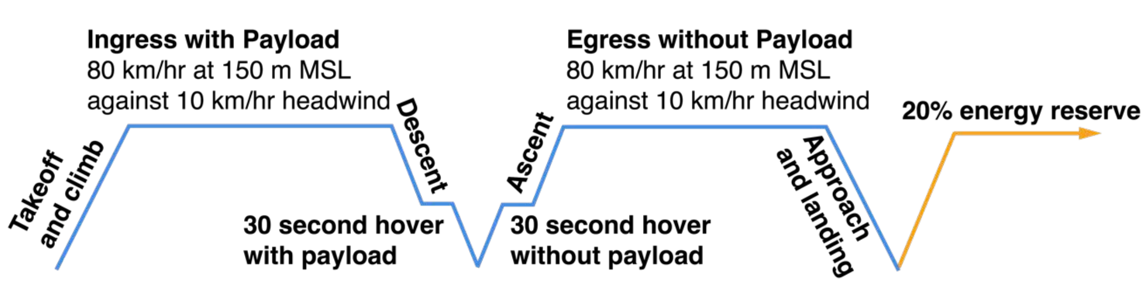
The primary outputs of interest are the energy consumptions and masses of delivery drones that are *converged*: They have been properly sized to carry all the payload and onboard systems. We used fixed-point iterations to converge the empty weight of the drone designs.

In the following sections, we discuss the mission we used, the performance model, and the results of the model.

Notional Delivery Mission

We use the published performance goals of the Amazon Prime Air (shown in Figure 3.1) as the notional delivery drone mission. Here the drone must fly at 80 km/hr at about 150 m (or about 400 ft) (Amazon, undated). The delivery mission illustrated in Figure 4.1 is composed of two cruise segments and two 30-second hover segments, one with and one without payload. The hover segments account for the time the drone might need to (1) approach and maneuver around dense areas, (2) find suitable landing or drop-off areas, and (3) coordinate with the package recipient. In practice, the hover is energy-intensive and should be minimized with preplanning and high-fidelity topological data.

Figure 4.1. Notional Delivery Drone Mission for Computing Energy Use



SOURCE: RAND author’s calculations.
NOTE: MSL = mean sea level.

While the mission energy consumption is computed assuming that the package is successfully delivered, the actual vehicle battery is sized for the more strenuous case where delivery fails and the drone has to return with the package. Similarly, while we assume a 10-km/hr headwind in cruise for computing energy use, the batteries are sized to sustain a stronger 20-km/hr headwind each way. Finally, we add a 20-percent energy reserve on top of all of the previous margins to minimize unplanned landings. Setting up emergency landing areas on rooftops (with wall plug access) or near electric ground-vehicle charging areas can moderate this reserve requirement.

Performance Model

To compute the energy consumption for cruising, we extend D'Andrea's (2014) simple model derived from the generalized Breguet range equation, which, as discussed in Chapter Three, relates aircraft flight efficiency to aerodynamic and structural efficiencies. This model accounts for the high-level impacts of aerodynamic efficiency, battery-specific energy, and expected headwinds on delivery drone sizing and flight efficiency.

Rather than simply assuming a fixed empty weight fraction, as was the case in the original model, we perform a coarse weight accounting to include the effect of power requirements on electric-motor sizing. The cruise and hover efficiencies are computed based on idealized actuator disk theory, adjusted empirically to account for nonideal rotors. Finally, the motors are sized for worst-case limited-power conditions (including thrust-to-weight reserves for control) and we assume prevailing motor and motor controller efficiencies and specific powers.

Applying the Performance Model: Two Design Case Studies

We apply the performance model to two design case studies: (1) a baseline design representative of what is possible with today's technology and (2) a more advanced design expected to enter service in five years. We compare the input parameters and assumptions of the two designs in more detail in the appendix.

Baseline Design

The baseline delivery drone design is roughly in the same class as the published Amazon Prime Air vehicle (shown in Figure 3.1). Like the publicized Prime Air vehicle, the vehicle design follows a hybrid multicopter configuration with dedicated hover-and-cruise motors and offloads lift load to the wings in cruise. The drone is powered by eight dedicated lift rotors grouped in four counter-rotating banks, as well as by two counter-rotating cruise motors. Onboard avionics and sense-and-avoid systems are assumed to consume 0.1 kW. (For reference, a powerful contemporary laptop takes about 0.1 kW to power.)

We assume a relatively modest L/D of 3. This aerodynamic assumption is bounded above by the L/D of 4.0–5.5 achieved by both conventional helicopters and compound helicopters (helicopters with wings).

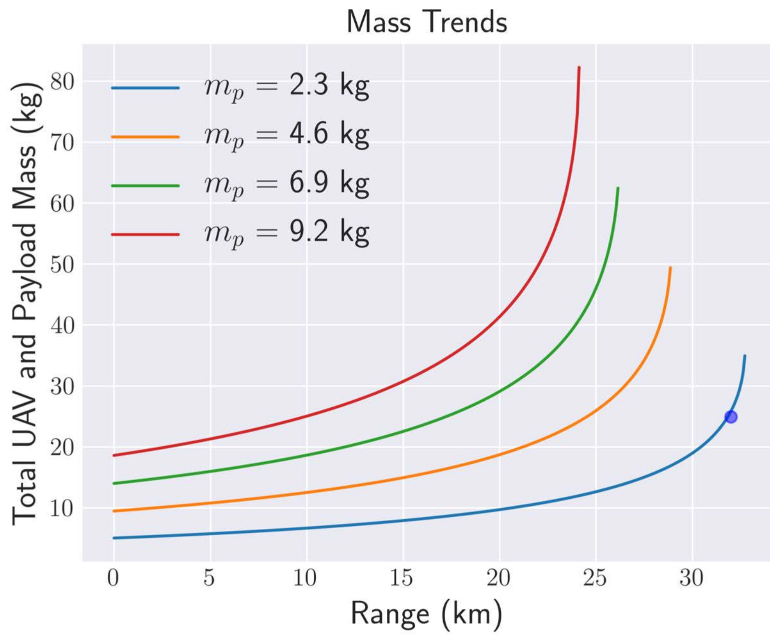
The airframe structure is assumed to account for 35 percent of the total takeoff mass, which is consistent with the structural efficiency achieved by conventional aircraft. A further 15 percent of the takeoff mass is dedicated to mechanical, electrical, and power electronic subsystems, while another 400 grams are dedicated to avionics and sensors.

We assume a cell-level battery energy density of 260 Wh/kg based on the energy density of contemporary, industrially produced lithium ion cells for electric cars and laptop computers. Electric-vehicle batteries have a *packing efficiency* (i.e., the ratio of power-cell to overall battery-pack weight) of 65 to 75 percent. The additional 25 to 35 percent of weight accounts for battery structure, enclosure, and thermal control. Weight efficiency matters more in aerial than in terrestrial applications: We "pay" for every unit of lift generated with induced drag. For the baseline delivery drone, we assume a conservative 75-percent battery-packing efficiency, one that is on the more efficient side of what can be achieved in electric cars. We also assume a further equivalent energy density degradation of 20 percent to account for loss in capacity over time and in nonideal operating temperatures. The effective gravimetric, battery-specific energy of the full-up battery system is then about 150 Wh/kg.

Baseline Design Results

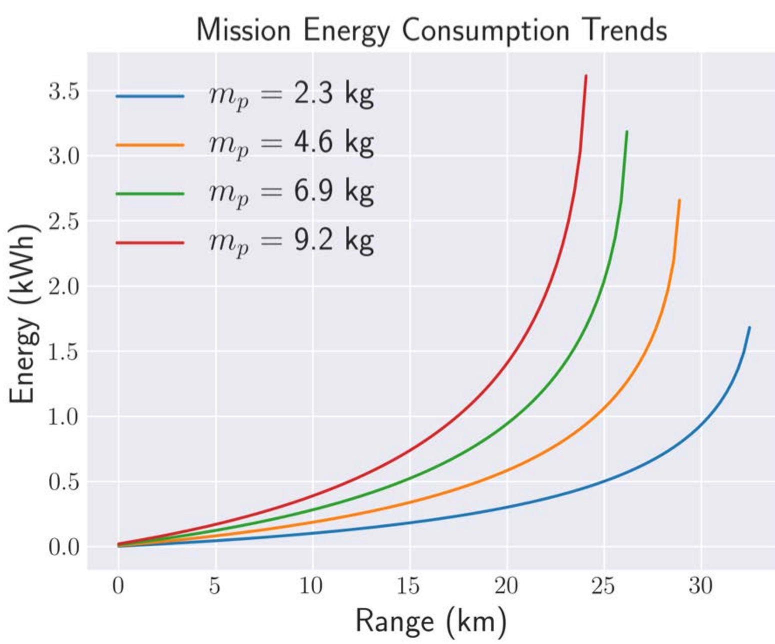
The UAV mass and energetics results of the baseline design case study are shown in Figure 4.2. Each curve captures the mass and energy consumption trends of a family of converged design with different range capabilities for the same payload mass. The payloads are at multiples of 5 lb (or 2.3 kg). Nonconverged designs are not shown. Thus, these curves delimit the boundaries of today's delivery drone design space.

Figure 4.2. Baseline Design Drone Mass Trends



NOTE: The blue dot marks the published range and mass figures for the Amazon Prime Air Drone (as of 2016) with a 10-mile (16.1-km) operating radius or 20-mile (32.2-km) range and a 5-lb (2.3-kg) payload capacity (Amazon, undated). m_p = mission payload.

Figure 4.3. Baseline Design Drone Energy Consumption Trends



As one might expect, both UAV mass and energy consumption grow dramatically as the range requirement increases. While most aircraft show a super-linear increase in energy use as range and payload capacity increase, the lower energy density of batteries makes this trend more pronounced. We observe that technical and design limitations constrain all of the vehicles to a maximum range of 25 to 35 miles, depending on payload. There is certainly room for improvement aerodynamically: A higher L/D, as we shall see in the next section, could significantly boost both range and payload performance. But it is also worth noting that, given the small footprint of many cities, a range of 25 to 35 miles may well be sufficient.

The blue dot in Figure 4.2 marks the published mass, range, and payload parameters of the Amazon Prime Air drone. Our model predicts a very similar vehicle mass to the Amazon design of 55 lb for matching payload (5 lb) and range requirements (10-mile radius). The important takeaway here is that the performance of the Amazon drone as it is designed is close to the limit of what is possible with today's lithium ion battery technologies and hybrid multicopter configuration. More-advanced configurations with improved aerodynamics are needed to increase performance.

Our model predicts that the baseline drone would consume about 1.5 kWh of energy to perform a delivery mission at its maximum range. For context, this is the same amount of energy needed to run a window-mounted air-conditioning unit for an hour. Another way to think about the energy consumption of the delivery drone is to relate it to the efficiency of ground vehicles. To make the comparison more consistent, we can measure the specific energy intensity, expressed in terms of the energy consumption (e) normalized by the product of the mission payload (m_p) and range (R):

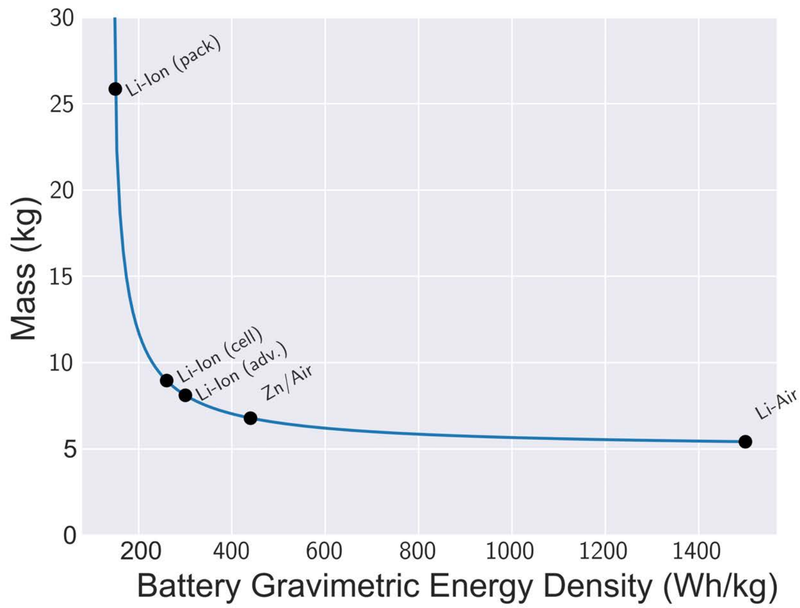
$$\eta = \frac{e}{m_p R} \qquad \text{Eq. 4.1}$$

Using the above efficiency metric, we find that the baseline drone achieves a specific energy intensity of about 20 Wh/kg/km, or about 0.07 megajoules (MJ)/kg/km. As a point of comparison, an average passenger car consumes about 2.32 MJ/passenger/km (Davis et al., 2016), or about 0.038 MJ/kg/km if we assume a single passenger with an average mass of 62 kg. The equivalent gas mileage for the baseline delivery drone is about 460 miles per gallon equivalent (MPGe) using the U.S. Environmental Protection Agency's (2011) metric of 33.7 kWh of energy per gallon of gasoline.

As with aircraft, the energy consumption rate is nonlinear with respect to the designed range. If we halve the required delivery radius to 8 km and redesign the drone, then the energy consumption to deliver a 5-lb package falls to only 0.4 kWh, or less than 30 percent of the baseline design.

The design is also highly nonlinear with respect to battery gravimetric capacity. In Figure 4.4. we hold all design parameters constant except for the battery density for the baseline design and plot the variation in converged UAV outcomes. We also superimpose the likely capacity of advanced battery chemistries, such as zinc-air and lithium-air batteries, on the plot.

Figure 4.4. Converged Baseline UAV Mass as a Function of Battery Gravimetric Energy Density



NOTE: The average energy densities of lithium ion (package and battery only) and expected densities of advanced battery chemistries (zinc-air and lithium-air) are overlaid. Li-Ion = lithium ion. Zn/Air = zinc-air. Li-Air = lithium air.

The results in Figure 4.4 show that, for UAVs that achieve the baseline design goals of delivering 5 lb to a radius of 10 miles, there is indeed a preverbal "knee in the curve" in UAV mass with respect to the battery energy density. The mass of the drone may be expected to decrease dramatically with even evolutionary advances in battery energy density. The expected vehicle mass reduction from dramatically denser future battery chemistries, such as lithium-air, saturates for the very short delivery range in question. Exotic chemistries, such as lithium-air, are instead expected to enable delivery of heavier packages over longer distances.

Advanced Design

We now consider the performance of a more advanced delivery vehicle that could be developed within five to ten years. This vehicle has improved aerodynamics and structural and propulsive efficiency. It achieves much better operating efficiencies and can potentially be used for longer delivery flights with multiple stops.

We estimate the L/D of the advanced delivery drone using the aerodynamic efficiencies of analogous fixed-wing VTOL aircraft. Our assumption is that future delivery drones will be carefully designed to combine our knowledge about VTOL design in conventional aircraft and the best attributes of distributed electric propulsion. Two proxies are shown in Figure 4.5: the turboshaft-powered AgustaWestland AW609 tilt-rotor (the civilian derivative of the military MV/CV-22 Osprey) and NASA's unmanned GL-10 hybrid-electric tilt-wing demonstrator (Fredericks, Moore, and Busan, 2013).

Figure 4.5. The AgustaWestland AW609 and NASA's GL-10 Demonstrator

AgustaWestland AW609 (Wikipedia)

NASA GL-10 Tilt-Wing Demonstrator (NASA)

SOURCES: (Left) Photo by Dmitry Mottl via Wikimedia Commons; (right) NASA Langley photo by David C. Bowman.

In the appendix, we estimate the full-scale AW609 to have an L/D of about 7.9. We then aerodynamically scale this value down to the size of a likely delivery drone, which yields an L/D of 5.6. This configuration corresponds to either a well-designed, clean tilt-rotor configuration generally similar to the AW609 or a multi-rotor design with hover rotors that can be folded in cruise to reduce drag. NASA's GL-10 design, which is somewhat closer in size and configuration to a hybrid multicopter delivery drone, has a much higher cruise L/D of 20 as its design objective (Fredericks, Moore, and Busan, 2013). However, the demonstrated value is not yet known. Thus, in the subsequent analysis, we use the more conservative value of 5.6.

We assume a 4-percent year-to-year improvement in battery energy density, which is conservative relative to historical trends and which aligns with existing research programs (Van Noorden, 2014). The assumed improvements lead to a cell-level energy density of 316 Wh/kg in five years. We further assume an increase in battery packing efficiency to 80 percent because of more-efficient integrated battery structures and air-cooled battery cells. For context, the Solar Impulse II, an ultra-efficient world-circling solar-powered aircraft, achieves a battery-pack efficiency of 93 percent (Solar Impulse, undated). We deem the Solar Impulse battery pack to be the upper bound of what is possible in the near future. We also include a lower averaged battery degradation factor over time of 10 percent (relative to 20 percent in the baseline case). The combination of improved energy density and packing efficiency yields an energy density of 228 Wh/kg for the advanced battery pack.

Other improvements—discussed in more detail in the appendix—include higher hover and cruise propulsive efficiencies from improved propeller design. It should be noted that the assumed figures of merit for the advanced design are still low compared with full-scale propellers (owing to adverse scaling effects on small-rotor profile drag). Elsewhere, the motor power density, onboard avionics weight, and power consumption, as well as the structure and systems mass fraction, all see modest improvements. Finally, we assume that optimally blended propulsive and aerodynamic control in the advanced design can reduce the required thrust-to-weight ratio (T/W) for hover from 1.5 to 1.3.

Advanced Design Results

The design results of the advanced drone families with the assumptions discussed in the previous section are shown in Figures 4.6 and 4.7.

Figure 4.6. Advanced Design Delivery Drone Mass Trends

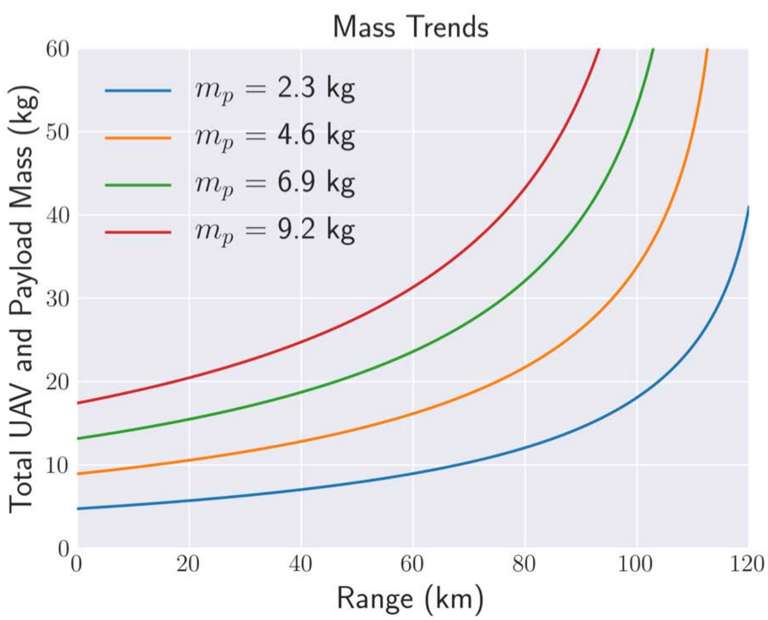
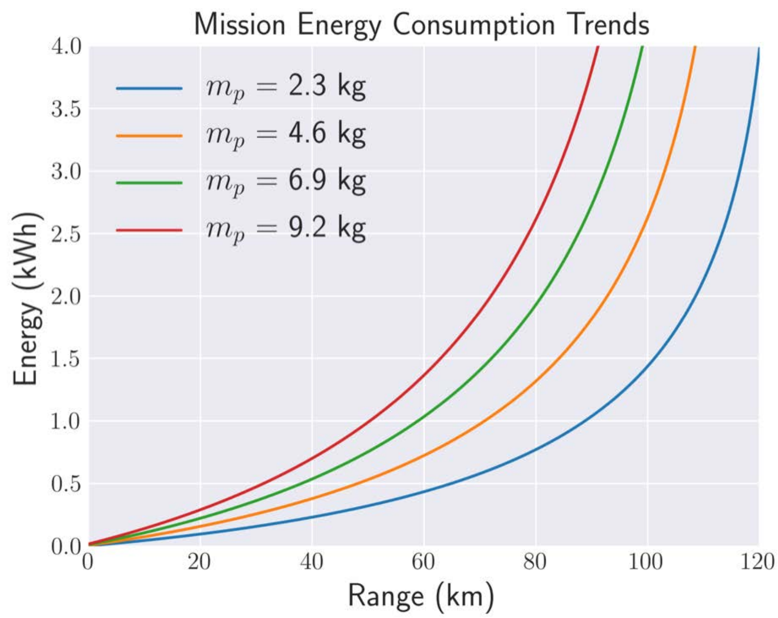


Figure 4.7. Advanced Design Delivery Drone Energy Consumption Trends



The first takeaway from the figures is that the substantial aerodynamic and propulsive improvements reduces both the mass and energy consumption of the delivery drones. In fact, Figure 4.6 shows that a 25 kg–class advanced drone can now deliver more than 9 lb of payload to the same 32-km range (10-mile radius) as the baseline vehicle. Alternatively, the same 25-kg advanced drone can deliver a single package to about 110 km (34-mile radius). The energy consumptions shown in Figure 4.7 show similar magnitudes of improvement.

We can also use the model to explore the potential of multi-stop deliveries enabled by the more-advanced drones. The requirements and performance for four single- and multi-stop vehicles are summarized in Table 4.1. In this scenario, each package is assumed to weigh 5 lb (2.3 kg). For each additional stop, we increased the required range by $0.5r_b$, where r_b is the radius of the baseline drone, or 10 miles (16.1 km). The required mission hover time also increases as a function of the number of stops. The idea is that rather than making the full out-and-back delivery trip, the multi-stop drone could deliver to a cluster of nearby destinations in one trip. This assumes a measure of dynamic route planning and coordination to optimize delivery efficiency.

Table 4.1. Example Multi-Stop Delivery Requirements

Number of Packages	Payload Mass (kg)	Range (km)	Drone Mass (kg)	Energy (kWh)	Energy/Package (kWh)
1	2.3	32.2	7.5	0.26	0.26
2	4.6	40.2	14.5	0.51	0.26
3	6.9	48.3	23.1	0.91	0.30
4	9.2	56.3	33.8	1.54	0.38

Table 4.1 shows that, compared with the baseline design, the mass of the advanced drone to perform the same single-stop delivery mission has fallen from 25 kg to 7.5 kg. The energy consumption to make one delivery has fallen to just 17 percent of that of the baseline drone discussed in the previous section.

Interestingly, when we consider multi-stop missions, the per-package energy consumption is unchanged as we go from making one to two deliveries and increases thereafter. Apparently, it would be inefficient to deliver more than two packages on one trip using even the advanced drone. There are several reasons why multi-stop operations scale poorly under our current assumptions:

1. **A longer-range vehicle carrying more payload requires more energy and batteries for each unit of distance traveled.** The larger multi-stop vehicle carries more batteries and payloads farther and pays for it in drag.
2. **The vehicles are sized conservatively to be able to traverse the entire delivery route and return to the fulfillment center with all packages undelivered.** The burden of undeliverable packages grows with each additional package carried and compounds with the additional 20-percent energy margin that we specified in the model.
3. **Our clustering assumption is likely pessimistic.** The increase in delivery range required for each marginal package is likely less than $0.5r_b$. Multi-stop delivery has to be motivated by sufficiently high density of demand. Indeed, if we relaxed the additional distance requirement to $0.25r_b$ (while holding all other parameters constant), then the multi-stop approach shows modest per-package energy gains at up to three packages.

Relaxing the constraints in items 2 and 3 could make multi-stop delivery viable for larger numbers of packages. Changing the battery chemistry to improve energy density can also make multi-stop delivery attractive. However, there are likely to be diminishing returns even for the advanced drone.

Chapter Five. Conclusions

In this report, we explored the vehicle design aspects of the delivery drone problem, focusing on energy consumption and weight. A brief analysis of the requirements shows that a 10- to 15-mile delivery radius is likely sufficient to cover most urban areas in the United States. A VTOL-capable delivery drone eases operations at the terminal area at a cost to cruise efficiency. The limited delivery range and payload requirements, coupled with the power efficiency of electric motors at small scales, makes VTOL viable. The scale-free nature of electric propulsion systems further reduces the cost of mounting separate and optimized cruise and hover motors. This helps to bridge the long-standing gap between good hover and cruise performance in VTOL aircraft (at least for small, short-range applications).

Simple integrated modeling of delivery drone performance shows that the Google Project Wing– and Amazon Prime Air–type delivery drones represent the limit of what is possible when assuming a simple, moderately efficient hybrid multicopter configuration and today's battery energy density. For this class of drones, we estimate the energy to deliver a 5-lb payload out to a radius of 10 miles to be about 1.5 kWh.

Looking forward, more gains are possible with aerodynamic refinements and improved batteries. The combination of higher L/Ds (scaled from today's VTOL tilt-rotor designs), denser lithium-ion batteries, entirely different battery chemistries (lithium-air, for example), improved structural efficiencies, and blended aerodynamic and propulsive control could dramatically reduce energy consumption, leading to five- to sevenfold improvements in flight efficiency. Improved flight efficiency could support multi-stop delivery drones, which could be more efficient but may also require sufficiently dense delivery demands. While important aspects of small electric UAV aerodynamics, aeroacoustics, and flight control are underresearched in relation to more-established commercial and general aviation aircraft, as the market grows for higher-performance delivery and other commercial systems, we can expect a reorientation of aerospace engineering research and development, as well as education to answer this important and growing research question.

Appendix. Summary of Modeling Assumptions

Performance Model Assumptions and Parameters

The predictions made by our simplified delivery drone performance model rest on a number of important assumptions. We document the assumptions and parameters for the baseline and advanced drone configurations in Table A.1.

Table A.1. Major Parameters and Assumptions of Two Notional Delivery Drones

Parameters/Assumptions	Baseline	Advanced
Aerodynamics		
L/D (glide ratio)	3	5.6
Power and Propulsion		
Electronics power (kW)	0.3	0.25
Battery-specific energy (Wh/kg)	195	253
Hover figure of merit	0.6	0.65
Cruise power ratio (ideal to effective)	0.65	0.7
Motor and controller efficiency	0.93	0.93
Motor-specific power (kW/kg)	8	10
Propeller radius (m)	0.4	0.4
Number of hover motors	8	8
Number of cruise motors	2	2
Design energy margin (%)	20	20
T/W hover	1.5	1.3
Mass		
Avionics mass (kg)	0.4	0.35
Airframe mass (%)	33	33
Systems mass (%)	10	10
Design mass margin (%)	10	10

Estimating the Lift/Drag Ratio of the Advanced Configuration

In this section, we try to determine the possible L/D of the advanced VTOL delivery drone by estimating and scaling the aerodynamic performance of the AW609 tilt-rotor aircraft.

The simplified scaling assumes a proportional (self-similar) shrink of the AW609 to the size of a delivery drone. Clearly, this analysis ignores the fact that the two configurations will be substantially different. However, proportional scaling should still provide a reasonable estimate of what is aerodynamically possible with a properly executed design.

The first step is to estimate the cruise L/D of the full-scale AW609. We obtained the relevant aircraft characteristics from the AW609 flight test presentation (Venanzi and Wells, 2013), as shown in Table A.2.

Table A.2. AW609 Tilt-Rotor Weight and Performance Specifications

Performance Specifications	
Takeoff weight	16,800 lb
Fuel weight	2,570 lb
Shaft-specific fuel consumption	0.507 lb/hp/hr
Range with full passenger load	500 nmi

NOTE: hp = horsepower.
SOURCE: AgustaWestland, undated.

Assuming that taxi and takeoff take 3 percent of the fuel reserve and unusable fuel accounts for another 10 percent, we arrive at a weight fraction (w_i/w_f) of 1.15.

The PT6C-67D turboshaft, which is similar in technology and power output to the PT6C-67A engines used in the AW609, has a brake shaft–specific fuel consumption (BSFC) of 0.507 lb/hp/hr. The BSFC measures the efficiency at the engine shaft. To get the power output at the propellers, we further assume a combined transmission and aero-propulsive integration loss of 8 percent and a modest propeller efficiency of 75 percent, which reflects the compromises that must be made between cruise and hover performance in a tilt-rotor aircraft. Plugging these terms into the unit-consistent Breguet range equation (BSFC in lb/hp/hr and range in nautical miles) for propeller-powered aircraft below and solving for the cruise L/D yields a value of 7.9.

$$R = 236 \frac{\eta}{BSFC} \frac{L}{D} \ln\left(\frac{W_i}{W_f}\right) \qquad \text{Eq. A.1}$$

The second step in the aerodynamic estimation is to scale the AW609 L/D results down to the likely dimensions of the delivery drone. Viscous scaling can substantially affect the aircraft profile drag C_{D_p} through the skin friction coefficient C_f. The profile drag accounts for about one-half of the aircraft drag in cruise and can be expressed for the different aircraft components (wing, fuselage, etc.) in terms of some empirical form factor k and the ratio of wetted to reference areas (S_{wet}/S_{ref}):

$$C_{D_p} \propto k C_f \frac{S_{wet}}{S_{ref}} \qquad \text{Eq. A.2}$$

If we assume proportional scaling, where the relative dimensions of the aircraft components do not change, then the form factor and area ratios remain constant. The profile drag ratio between two self-similar aircraft *a* and *b* reduce to the ratio between their skin friction coefficients:

$$\frac{c_{D_{p_a}}}{c_{D_{p_b}}} = \frac{c_{f_a}}{c_{f_b}} \qquad \text{Eq. A.3}$$

The skin friction can in turn be expressed using the Reynolds number, the well-known Prandtl-Karman relationship, and Sutherland's viscosity laws as functions of the Mach number, altitude, and the component length scale (Kroo and Shevell, 2001). We estimate the AW609 wing chord length by inspection to be about 4.8 ft. The vehicle fuselage is 44 ft long. The aircraft cruises at Mach 0.43 at 25,000 ft. These parameters yield an estimated wing and fuselage C_f of 0.00305 and 0.00216, respectively.

For the delivery drone, we assume a fuselage length of 8 ft and a wing chord of 1.5 ft. The drone flies at Mach 0.065 at 400 ft. This yields a wing C_f of 0.00473 and a fuselage C_f of 0.00346. This means that the average wing and fuselage C_f ratio; therefore, the profile drag ratio between the delivery drone and the AW609 is about 1.55. We apply another 10-percent increase to the profile drag ratio of the drone to account for the relatively larger impact of manufacturing imperfections, antennae, and other surface protrusions on its viscous drag. This brings the profile drag ratio to 1.7.

Finally, assuming that 50 percent of the aircraft drag comes from profile drag and assuming that the lift-dependent component increases by 10 percent to account for boundary layer growth and super-velocity, we end up with a 1.4-fold increase in total drag for the delivery drone, or a L/D of 5.6.

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