

Regulatory Implications for Unmanned Aerial Vehicles in Last-Mile Delivery

A Stakeholder Resource



Regulatory Implications for Unmanned Aerial Vehicles in Last-Mile Delivery

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Abstract

This report examines the legal, regulatory, and societal barriers facing unmanned aerial vehicles (UAVs) as they are deployed for last-mile delivery with a particular focus on deployment in the United States (U.S.). The status quo for current legal and regulatory restrictions is first explored followed by a discussion on miscellaneous regulatory issues and areas of uncertainty that are likely to challenge unmanned aerial vehicles for last-mile delivery (UAV-LMD) deployment. This is followed by an evaluation of potential societal barriers imposed on UAV-LMD and the likely regulatory pathways through which these barriers will manifest. This report offers a nominal set of restrictions likely to limit operators and their fulfillment network planning and strategic design.

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Introduction



1 Introduction

Over the past decade, the logistics industry has experienced substantial growth and its fair share of technological disruption. Particularly in suburban and urban settings, consumer demand for same-day or two-hour delivery has ballooned and companies have struggled to meet demand without incurring substantial last-mile delivery costs. The last-mile is defined as the final few stages of a parcel's delivery chain process which typically happens in the congested neighborhoods of today's mega-cities. Whilst shifting consumer expectations have played a pivotal role, a symbiosis of trends has driven immense

growth in last-mile delivery operations: intensifying urbanization, increased purchasing power of the global middle class, the rise of new digital retail business models, the shift from commercial to private parcel consumer demand, and advancements in delivery vehicle and routing technologies (Joerss et al., 2016a). In the U.S., e-commerce players continue to grab market share with online sales' outpacing offline sales' growth with compound annual growth rates (CAGRs) of 16% and 4% from 2012 - 2021 respectively, shown in Figure 1 (Young, 2021).

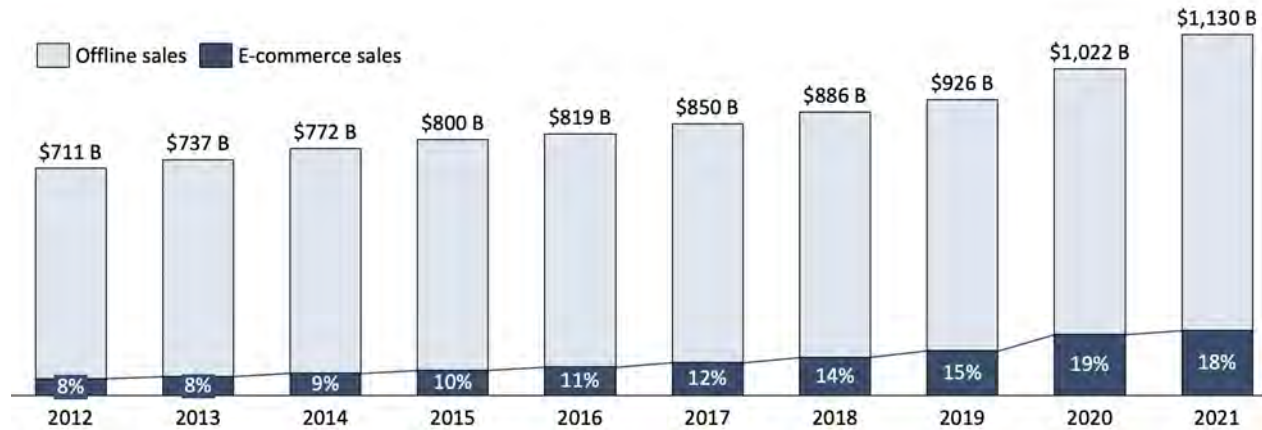


Figure 1: U.S. online versus offline sales as a percentage total of retail spend in \$B, 2012-2021.

The global cost of parcel delivery, excluding pickup, line-haul and sorting costs, cur-

rently amounts to approximately \$80B annually with China, Germany and the U.S.

representing 40% of this demand. Not only is the last-mile market large, it is also grow-

ing with recent annual growth rates are between 7-10% for developed countries but almost 300% in developing countries like India (Joerss et al., 2016b).

The last-mile in a delivery chain is vitally important to firms because it constitutes a disproportionately large share of the parcel delivery cost to a customer, partic-

ularly in urban areas, as shown in Figure 2 (Joerss et al., 2016a; Jacobs, 2019). From the perspective of a logistics firm, this problem currently represents an opportunity to differentiate one's services and products from other logistics specialists but also capture more commercial customers that previously managed their own logistics op-

erations in-house. Amazon, United Parcel Service (UPS), Google and FedEx, among others, are investing heavily in new operational models, technologies, and scientific brain-power to address society's urban logistics woes.

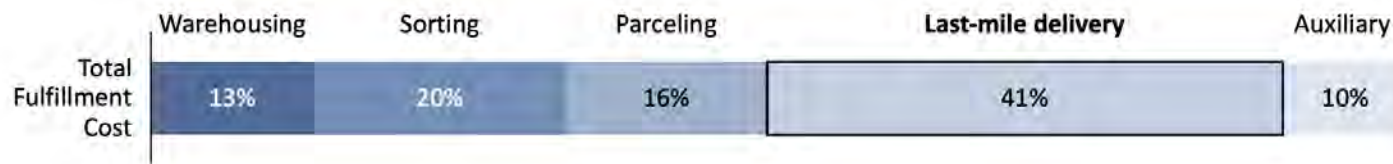


Figure 2: Survey of typical U.S. last-mile cost as a percentage of overall fulfillment cost.

The last-mile is also a significant contributor to the broader negative sustainability externalities associated with urban logistics, be it economic, social or environmental (Deloison et al., 2020). In today's mega-cities, the face of urban last-mile logistics has changed.

In half a century, an industry that used to be a peripheral part of daily life has morphed into one patent to every urban consumer. But whilst the last-mile problem is a global one, much of the early investment is being allocated to projects in the U.S. With

this in mind, this report will focus solely on the state of the last-mile in the U.S., with a handful of allusions to international enterprise.

1.1 UAVs for Last-Mile Delivery







Due to these key factors, significant market demand exists for new approaches to last-mile delivery that ameliorate the imparted negative externalities and meet increasingly demanding customer service level expectations. Last-mile players are looking to integrate a host of small solutions to achieve the larger objective of efficient urban logistics. Aggregated demand solutions such as parcel lockers and public drop-off points are already being deployed – an ironic reflection of the “traditional” logistics operational models prior to the e-commerce boom. Multi-echelon delivery solutions are also becoming more common in today’s mega-cities as large parcel trucks becoming increasingly ill-suited to navigate today’s dense suburban and urban spaces be it because of congestion, urban built density or unfavorable regulation. But one technol-

ogy that has received substantial public attention in the past decade for last-mile delivery is the UAV, colloquially referred to as a drone. UAVs not only have the potential to revolutionize the last-mile industry, but the estimated market size is immense, calculated to exceed \$127B globally (Deloitson et al., 2020). UAVs are unique in three ways: low per-vehicle capital expenditures (CAPEX) costs, autonomous delivery capabilities and the ability to rapidly travel point-to-point. These three qualities contribute to the growing popularity of UAVs in the last-mile space.

The key challenges that face the mainstream deployment of UAV-LMD are regulation, technological advances to increase their flight range and enable a smoother integration of UAVs into the existing airspace safety frameworks, and social adoption and




acceptance. Since its inception, however, UAV-LMD players, from incumbent last-mile companies to various hardware-, software- and/or operations-focused startups have approached the problem in notably different ways, see Table ???. But regardless of their differences – their engineering (UAV designs, level of automation, UAV power-plant decisions) to their operations strategy to their target market segment – players will need to contend with the same reality and its host of real-world constraints. This report sits at this nexus: it formulates hypotheses on the real-world constraints facing UAV-LMD and takes a systems-level approach to studying their implications for the viability of commercial operations.

Table 1: Overview of the key UAV-LMD industry players.

Company	Description	Competencies
	<p>Amazon first broached their pursuit of UAVs for last-mile delivery in 2013. Within Amazon Prime Air, the company developed UAV hardware, software and operational know-how and pushed the FAA to permit commercial UAV testing operations BVLOS. Nevertheless, Amazon began testing in more favorable regulatory environments in Cambridge, UK and Vancouver, CA.</p>	<p>UAV hardware On-board software Logistics systems Regulation Advocacy</p>
	<p>UPS launched UPS Flight Forward in 2019 but began early testing of their truck-and-drone delivery system, Workhorse Workfly, as early as 2017. In October 2019, UPS were to first to gain FAA full Part 135 Standard Certification, allowing the company to operate a fully remote UAV delivery network across the United States with an unlimited number of UAVs launch hubs, both day and night.</p>	<p>UAV hardware On-board software Logistics systems Regulation Advocacy</p>
	<p>Early in 2014, DHL unveiled their UAV delivery service, announcing their in-house Parcelcopter design in parallel. It was the first to commercially integrate UAV deliveries into their broader logistics network, providing service to remote towns in Germany with a focus on medical supplies and small goods. Now in its fourth iteration, the Parcelcopter has evolved in configuration, payload capacity, range and use-case.</p>	<p>UAV hardware On-board software Logistics systems Regulation Advocacy</p>
	<p>Originally headquartered in Australia, Flirtey partnered with the University of Nevada as it relocated to United States focusing on UAV technology and the UAV-LMD logistics system development. They performed the first FAA-approved commercial UAV delivery in July 2015. Flirtey held partnerships with 7-Eleven (U.S.) and Domino's Pizza (New Zealand), in cases fully integrating the service chain from customer orders through to delivery.</p>	<p>UAV hardware On-board software Logistics systems</p>
	<p>Founded in 2011, Matternet provides end-to-end UAV-LMD offerings to customers. First championing the truck-and-drone delivery model in partnership with Mercedes-Benz Vans, Matternet has since pivoted into pure-play UAV-LMD with standing partnerships with UPS and Japan Airlines. Most recently, Matternet announced a stand-alone medical goods delivery service in Labor, Berlin, DE, as the first urban BVLOS operation globally.</p>	<p>UAV hardware On-board software Logistics systems</p>
	<p>Wing's parent company, Alphabet, has been investing in UAV delivery via its R&D subsidiary, Google X, since 2012. Wing soon showcased their lift+push UAV design and winch delivery technology. Testing in Logan City, AU and Virginia, U.S., Wing has been working with regulators and the public to inform UAV design, operational decisions and their in-house UTM platform.</p>	<p>UAV hardware On-board software Logistics systems Regulation Advocacy UTM/ATC</p>

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Company	Description	Competencies
	The Chinese e-commerce giant launched their UAV delivery venture in 2015 with initial investments into UAV hardware. With a focus on remote regions across China, by the end of 2017, JD.com had already performed thousands of deliveries across outer-Beijing and other provinces. The CAAC permitted JD.com to build out UAV landing platforms across the country.	UAV hardware On-board software Logistics systems Regulation Advocacy Infrastructure
	Founded in 2013, this software-focused Israeli company developed the first cloud-based UAV delivery service and operations management system. The latter system enables suppliers to leverage Flytrex’s fleet of UAVs as a shared resource with access to positioning, capacity, range and other live data. Since 2016, Flytrex have announced pilot programs in Ukraine and Reykjavik, IS to provide BVLOS autonomous UAV-LMD service.	UAV hardware On-board software Logistics systems Cloud integration
	In partnership with the Rwandan government, Zipline launched a national UAV delivery service in 2016 to supply remote health facilities. They offer an in-house fixed-wing UAV design, novel launch and retrieval mechanisms, remote BVLOS connectivity and delivery via parachute. Designed around the needs of local doctors, the service is integrated into existing SMS networks. In 2020, Zipline announced a new partnership with Walmart, U.S.	UAV hardware On-board software Logistics systems

1.2 Realizing the Impact of Commercial UAV Deployment

Full-scale commercial deployment of UAV-LMD promises to fill urban skies with fleets of package-carrying UAVs flying at low altitudes and at high speeds in close proximity to the many hazards present in today’s

mega-cities. However, despite the vision and effort of numerous last-mile players over the past decade, UAV-LMD has not yet materialized in this way. The non-existence of these services evinces the fact that there ex-

ist significant barriers and operational constraints that continue to bar successful commercial ventures. This report explores the host of hurdles and challenges facing UAV-LMD today. It does so in two ways:

1. Legal and Regulatory Barriers: This report analyzes the status-quo of applicable regulation in the U.S. and their related legal interpretations. In light of emerging consumer and industry interest in UAV-LMD, many regulatory and legal questions have surfaced in the past decade and, only recently, has apposite regulation been put in place to offer guidance. That goes without saying that there have been numerous cases already where regulation, societal norms and nascent UAV-LMD operations have prompted legal action. The relevant

regulation will continue to evolve as the industry scales, so a survey of remaining areas of regulatory uncertainty is also necessary.

2. Societal Barrier: This report explores UAV-LMD's potential societal externalities through a historical lens of low-altitude aerial operations. It also surveys current opinions of academics and industry stakeholders (regulators, commercial players and thought-leaders) to gauge their viewpoints and philosophies that capture society's potential concerns.

This report summarizes these challenges and assesses how they will shape future UAV-LMD operations. Thus, this report attempts to synthesize these constraints to determine which are directly relevant to UAV-LMD routing decisions and which are not. Figure 3 conveys the structure of this report

and the topics it discusses diagrammatically. Note, whilst this report attempts to provide a comprehensive structural overview of the relevant societal and regulatory constraints to UAV-LMD, it does not claim to pose recommendations for regulators, operators or active members of the public. It summa-

rizes the current status quo and, in places, suggests ways to conceptualize specific constraints. These suggestions are simplifications of the constraints for comprehension and ease of modeling purposes, not surmises of how any particular constraint will materialize in future UAV-LMD operations.

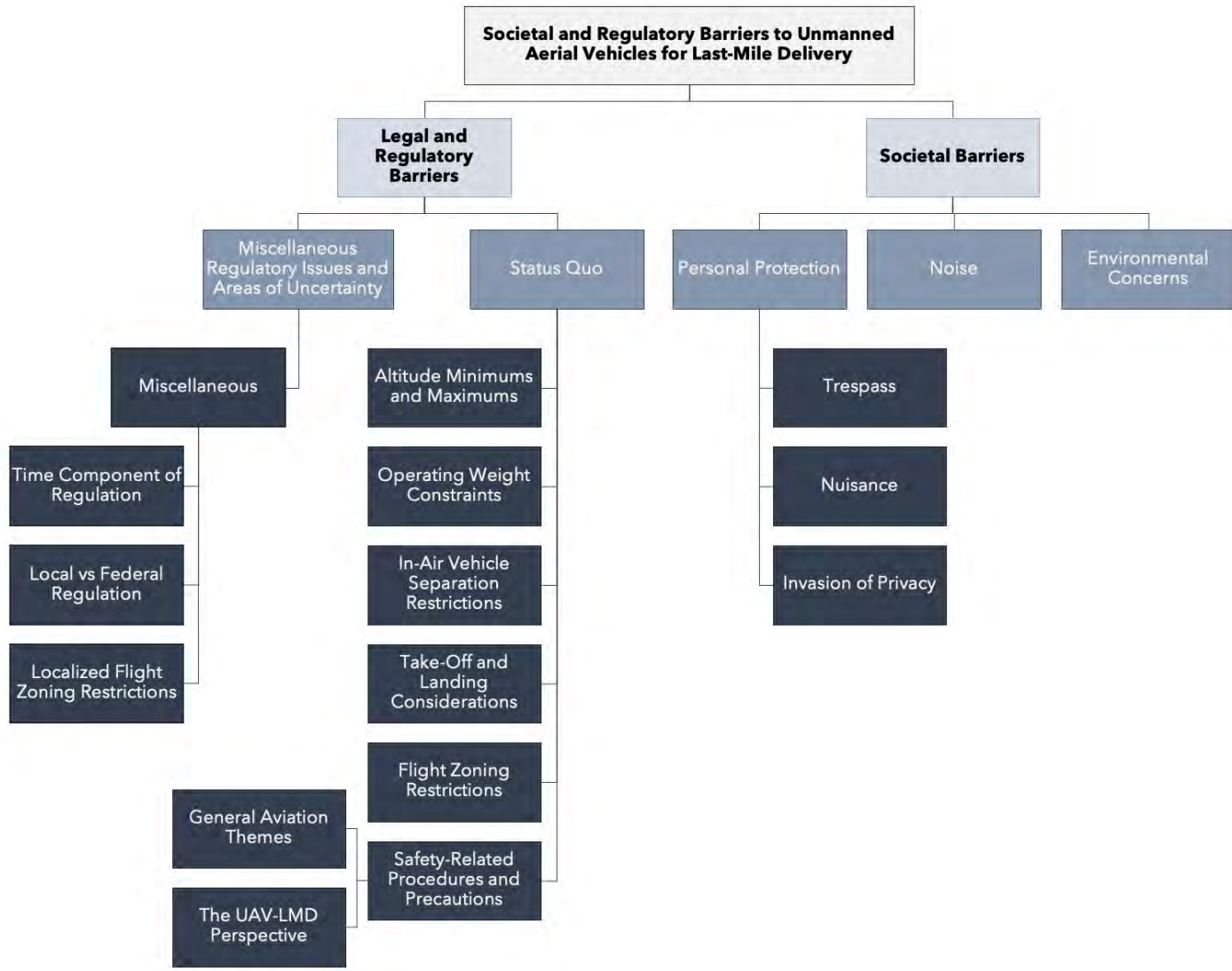


Figure 3: Overview of this report’s structure and analysis: social and regulatory barriers to unmanned aerial vehicles for last-mile delivery.

Legal and Regulatory Barriers



2 Legal and Regulatory Barriers

Over the past century the aviation industry has worked closely with local and national regulators to define what has become a complex set of airspace infrastructure and air traffic management protocols through national statutes, regulations, standardized best practices, legal rulings and analysis of aviation accidents. What has resulted is an airspace management ecosystem that offers efficiency and unmatched levels of safety and redundancy compared to other transportation ecosystems.

2.1 The Status Quo for Legal and Regulatory Barriers

The current state of air traffic control (ATC), airspace class definition and design, and aircraft operational rights is the product of decades of trial, error and litigation. Fast forward to 1958, the Federal Aviation Act established the FAA and made it responsible for the control and use of navigable airspace within the United States. The FAA created the The National Airspace System (NAS) to protect persons and property on the ground, and to establish a safe and efficient airspace environment for civil, commercial, and military aviation. Thus, all aerial vehicles operating in the airspace above the U.S. are expected to adhere to the appropriate operational, airspace and ATC constraints publicly enforced by the FAA. Figure 4 depicts the various airspace classes of the U.S. NAS (FAA Safety Team, 2020). Note

Widespread deployment of UAV-LMD promises to install multiple fleets of UAVs across various geographies operating numerous daily flights per day at low altitudes. Low-altitude aerial operations at this scale and breadth will represent an unprecedented and untested regulatory conundrum for local and national regulators alike. Please note that regulations in this sector are likely to be in continuous flux over the coming decades. Thus, this report highlights the possibility that any regulation quoted here may be re-drafted in the future.

that an aerial vehicle seeking entry to an airspace class must at a minimum liaise with the relevant ATC entity and adhere to a unique set of hardware and operational constraints.

Whilst medium- and high-altitude aircraft operations generally follow a homogeneous set of operational constraints across the U.S., operational constraints for low-altitude flight (generally assumed to be sub-5000 ft.) can vary dramatically from one location to the next. Whilst this is not supposed to be the case given the FAA's mandate to be the sole regulator of all navigable airspace in the U.S., this is predominantly due to the non-aviation-related constraints discussed in Section 3 and local best practices.



Figure 4: Airspace classification structure for U.S. NAS.

The most relevant existing FAA regulations that applies to UAV-LMD are housed in the FAA Part 107 Drone Regulations and FAA Part 135 Charter-Type Services (Rupprecht). Unlike Part 107 which was exclusively drafted for UAV flight, Part 135 is an already existing set of rules to govern inter-state and intra-state air delivery of mail and other goods. A UAV-LMD provider can certify its operations under either Part 107 or Part 135, however, each come with their unique set of constraints.

The key constraints that emerge out of a Part 107 certification are:

1. The UAV must be flown within visual line of sight (VLOS) of the pilot in command. This is very constraining for operators and the industry is pushing for regulations to permit extended visual line of sight (EVLOS) and eventually, BVLOS (FAA § 107.31 Part 107, 2020). Figure 5 depicts the differences between these terms, courtesy of Woo et al. (2018).
2. A UAV operator is mandatory for UAV flight, i.e. the UAV

cannot be autonomously flying. Furthermore, there is a strict one-to-one relationship between operator and UAV. Note that waivers have been granted that null this requirement for test purposes (FAA § 107.35 Part 107, 2020).

3. UAVs cannot be operated over a non-participating person, property populated with people or a moving vehicle, again another non-starter for urban UAV-LMD operations (FAA § 107.39 Part 107, 2020).
4. The UAVs cannot be operated in Class B, C, or D airspace and some definitions of class E airspace without an authorization or waiver. These classes are depicted in Figure 4.
5. Unless under a 107 waiver, if the UAV is to be considered under Part 107, it must weigh under 55 lbs. and remain under a 400 ft. altitude ceiling (Woo et al., 2018).

On the other hand, a Part 135 certificate can permit BVLOS operations. And the current FAA rhetoric is that Part 135 will continue

to be extended and adapted to accommodate for UAV-LMD by including additional constraints and adding exceptions to rules that do not apply to UAVs. With that said, those that seek to comply with Part 135 will need to meet a long list of requisites including aircraft certification, maintenance standards, operations manuals, training programs enactments, an Economic Authority certificate from the Department of Transportation, and insurance coverage for operations. Part 135 offers four types of certificates each with their own set of pros and cons, in order in general ease of certification:

- Single Pilot Certificate: a single-pilot operator is a certificate holder that is limited to using only one pilot for all Part 135 operations.
- A Single Pilot in Command Certificate: one pilot in command and three second pilots in command. There are also limitations on the size of the aircraft and the scope of the operations.

- A Basic Operator Certificate: a maximum of five pilots, including second in command pilots. A maximum of five aircraft can be used in their operation.
- A Standard Operator Certificate: fundamentally no limits on the size or scope of operations. However, the operator must be granted authorization for each type of operation they want to conduct (Federal Aviation Administration, 2022a).

However, in discussing the regulatory constraints applicable to low-altitude flight in more detail, one can distill current regulatory frameworks, be it Part 107, Part 135 or other relevant Federal Aviation Regulations (FAR)s under some broader operationally relevant constraints: operating weight constraints, operating altitude minimums and maximums, in-air vehicle separation restrictions, take-off and landing locations and procedures, non-airspace related flight zoning restrictions and safety-related procedures and precautions.

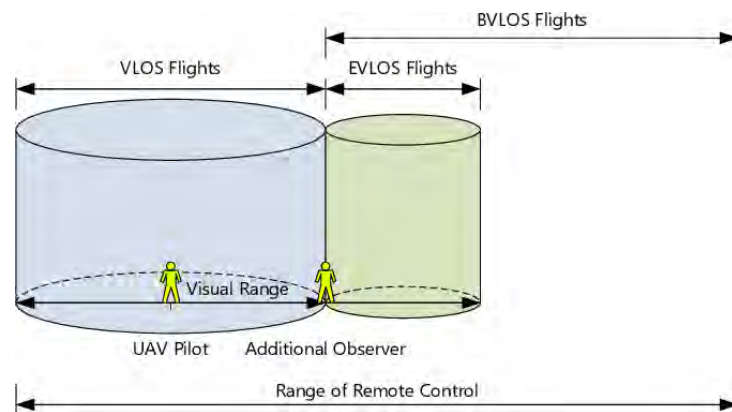


Figure 5: Visual illustration of visual line of sight terminology.

2.1.1 Operating Altitude Minimums and Maximums

The status quo for operating altitude constraints for general aircraft are prescribed via minimum altitude requirements in FAR Part 91

General Operating and Flight Rules §91.119, which states:

“Except when necessary for takeoff or landing, no person may operate an aircraft below the following altitudes:

- (a) Anywhere: An altitude allowing, if a power unit fails, an emergency landing without undue hazard to persons or property on the surface.
- (b) Over congested areas: Over any congested area of a city, town, or settlement, or over any open air assembly of persons, an altitude of 1,000 feet above the highest obstacle within a horizontal radius of 2,000 feet of an aircraft.
- (c) Over other than congested areas: An altitude of 500 feet above the surface, except over open water or sparsely populated areas. In those cases, the aircraft may not be operated closer than 500 feet to any person, vessel, vehicle, or structure.
- (d) Helicopters: Helicopters may be operated at less than the minimums prescribed in paragraph (b) or (c) of this section if the operation is conducted without hazard to persons or property on the surface. In addition, each person operating a helicopter shall comply with any routes or altitudes specifically prescribed for helicopters by the Administrator.” (FAA § 91.119 Part 91, 2020).

This is shown pictorially in Figure 6. Thus, this FAR suggests that minimum altitude requirements depend on both the vehicle type, population, and property density below the flight path and the ability of the pilot to safely execute an emergency landing without putting bystanders and property at undue risk. Interestingly, section (d) exempts helicopters from all altitude minimums except for the emergency landing contingency. This is also interesting since it does not capture any notion of noise, privacy, trespass or other non-aviation-specific legality concerns that are discussed in Section 3. Another interesting insight is the qualitative and subjective nature of the terms “congested” and “sparsely populated” which are often determined on a case-by-case basis. Varying legal interpretations of these terms

published by the FAA’s Office of the Chief Counsel in past case-law underscores how such language is commonly misinterpreted by operators, pilots, and legal practitioners alike (Reigel, 2008).

With all this said, these regulations are currently not applicable to UAV-LMD because UAV-LMD must be certified via FAA Part 107 at a minimum and Part 135 to permit broader BVLOS operations at scale. The aforementioned regulations are included to offer insight into the key drivers behind altitude minimums for general aircraft and, thus, what the key drivers for UAV-LMD are likely to be. Under the current regulations for UAV-LMD, FAA Part 107 stipulates that commercial UAVs cannot be flown above an altitude of 400 ft. without special permission from the FAA.

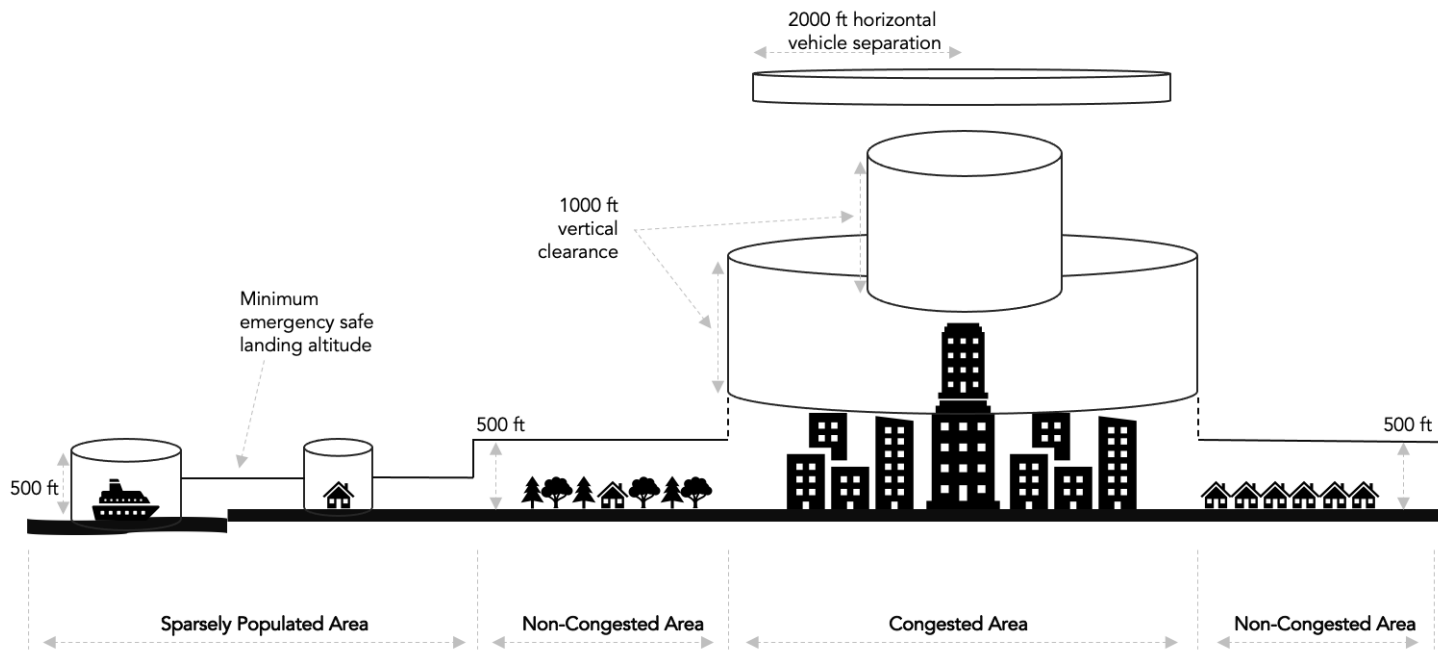


Figure 6: Pictorial depiction of current regulatory framework FAR Part 91 §91.119 for aircraft flight minimums.

Another reference point is the “Drone Integration and Zoning Act of 2019,” a bill introduced in the U.S. Senate on October 16, 2019 and reintroduced in 2021 which proposes the following key altitude

restrictions (Lee Utah, 2019). These restrictions are pictorially interpreted in Figure 7 and below:

- S.2607.3.e.1: “Nothing in this section may be construed to ... prohibit the Administrator from promulgating regulations related to the operation of unmanned aircraft systems at more than 400 feet above ground level;
 - (A) The Administrator [FAA] shall not authorize the operation of a civil unmanned aircraft in the immediate reaches of airspace above property without permission of the property owner.
 - ... in the case of a structure that exceeds 200 feet above ground level, the Administrator shall not authorize the operation of a civil unmanned aircraft –
 - (i) within 50 feet of the top of such structure; or
 - (ii) within 200 feet laterally of such structure or inside the property line of such structure’s owner, whichever is closer to such structure.
 - (B) The Administrator shall not authorize the physical contact of a civil unmanned aircraft, including such aircraft’s take-off or landing, with a structure that exceeds 200 feet above ground level without permission of the structure’s owner.
 - (C) The Administrator [FAA] shall ensure that the authority of a State, local, or Tribal government to issue reasonable restrictions on the time, manner, and place of operation of a civil unmanned aircraft system that is operated below 200 feet above ground level is not preempted.”

with the term “immediate reaches” defined as

S2607.2.4: “The term ‘immediate reaches of airspace’ means, with respect to the operation of a civil unmanned aircraft system, any area within 200 feet above ground level.”

and the term “reasonable restrictions” defined as

S2607.2.4.b.3: “reasonable restrictions on the time, manner, and place of operation of a civil unmanned aircraft system include the following:

- (A) Specifying limitations on speed of flight over specified areas.
- (B) Prohibitions or limitations on operations in the vicinity of schools, parks, roadways, bridges, moving locations, or other public or private property.

- (C) Restrictions on operations at certain times of the day or week or on specific occasions such as parades or sporting events, including sporting events that do not remain in one location.
- (D) Prohibitions on careless or reckless operations, including operations while the operator is under the influence of alcohol or drugs.
- (E) Other prohibitions that protect public safety, personal privacy, or property rights, or that manage land use or restrict noise pollution.”

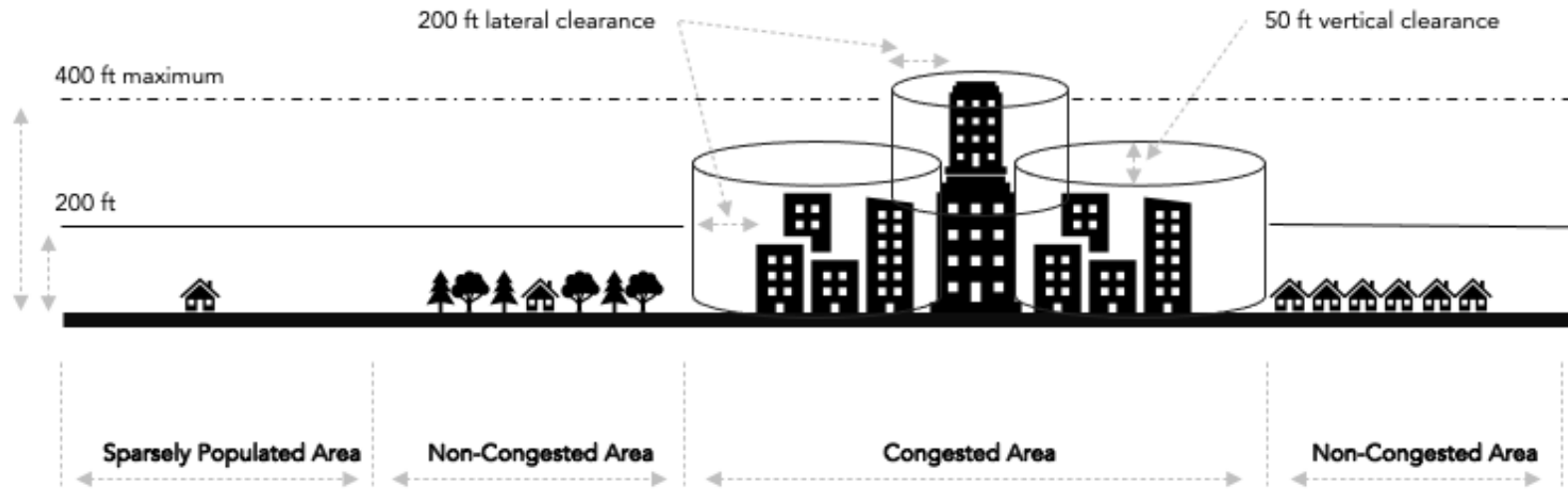


Figure 7: Pictorial depiction of suggested regulatory framework in “Drone Integration and Zoning Act of 2019” for aircraft flight minimums.

Whilst the “Drone Integration and Zoning Act” has not progressed past the bill introduction phase as of May 2022, its approach to and frameworks for UAV-LMD altitude minimums can offer a benchmark this report can build off of. In translation, the Act suggests that UAV-LMD should:

- not be permitted to fly above 400 ft.;
- not be permitted to fly in the immediate reaches of private property, defined as 200 ft. above ground level (AGL);

- not be permitted to fly within 50 ft. vertically and 200 ft. laterally of a structure that exceeds 200 ft. in altitude;
- be subject to state and local regulation below 200 ft. with the FAA reserving sole authority of regulation above 200 ft.

This structurally means that UAV-LMD is strictly limited to the altitude range of 200-400 ft. nationwide and is subject to local and state regulation in altitude ranges below 200 ft. It also means that UAVs are inherently limited in their ability to vertically scale struc-

tures that protrude into this altitude range if they do not offer 50 ft. of clearance between their roof and the 400 ft. altitude ceiling.

A key takeaway is that sub-200 ft. altitudes are emerging as an area of regulatory uncertainty. This is because minimum altitude constraints in these altitudes are likely going to be left to local regulators to manage and that their methodologies for defining such regulations will likely be driven by definitions of noise nuisance, privacy and trespass (discussed in Section 3) but also definitions of land-use zoning, perceived congestion levels, protected regions (such as schools or parks), and the eventuality of irregular public events. Many of these definitions are likely to differ between states and municipalities, making minimum altitude constraints all the more complex for UAV-LMD operators.

2.1.2 Operating Weight Constraints

Just as in the case of minimum and maximum altitude constraints, when it comes to operating weight constraints, how local and municipal regulators are likely to constrain operations is the most obvious area of uncertainty. The current status quo for operating weight constraints comes from FAA Part 107 which limits the UAV's max take-off weight (MTOW) to under 55 lbs. actually in the definition of what size vehicle can be legally certified under Part 107, quoted as

“Part 107 defines a small unmanned aerial system (UAS) as any uncrewed aircraft weighing less than 55 pounds” (FAA § 107.3 Part 107, 2020).

The FAA does offer a pathway to operate UAVs with MTOWs with more than 55 lbs. via what is termed a 49 U.S.C. 44807 grant of exemption whereby the operator must prove,

1. “Is in the public interest; and
2. Would not adversely affect safety or would provide a level of safety equal to that provided by the regulation.”
(Malecha, 2019).

It is noted that being granted this exemption is particularly difficult for UAVs because, as of now, the vehicles themselves do not go through a standardized and rigorous aircraft design and performance envelope certification process making proving (b) more difficult for operators. Figure 8 highlights the key weight dimensions – empty weight, max payload capacity and MTOW – for the major UAV-LMD hardware players. It is worth noting that the majority of players have designed vehicles subservient to the Part 107 MTOW limit of 55 lbs. by way of minimizing their vehicle's empty weight via aircraft design and by constraining their max payload capacity either artificially or via other dimensional constraints such as volume or safety. Amazon's delivery UAV is the only outlier here, likely because they possess a fleet of already weight-compliant UAVs and have designed their latest UAV expecting change in the MTOW constraint in future regulation.

Given this anticipated upper bound on weight of 55 lbs., at least in the near future, the next question to evaluate is if there is potential for tighter upper bounds that could further constrain operations. Looking to the “Drone Integration and Zoning Act of 2019”, one can

interpret the stipulation to answer this question.

S.2607.3.e.1.C: “The Administrator [FAA] shall ensure that the authority of a State, local, or Tribal government to issue reasonable restrictions on the time, manner, and place of operation of a civil unmanned aircraft system that is operated below 200 feet above ground level is not preempted.” (Lee Utah, 2019).

Firstly, the term “manner” could well provide grounds for local or state regulators to apply apply operating weight constraints that are more constraining than the FAA’s 55 lbs. MTOW limit. With that said, the bill is peppered with references to the 200 ft. boundary

between national airspace under the purview of the FAA and local regulators. If relevant regulation evolves along the lines of the bill’s rationale, the FAA will likely continue to dominate UAV-LMD regulation with limited authority outsourced to local regulators. Could local regulators restrict total operating weight for periods of a UAV’s flight trajectory that occur below 200 ft. such as take-off, delivery and landing? Whilst it remains unclear how courts will interpret this gray area, this report judges the likelihood that local regulators can further constrain total operating weight across a sufficiently large geographic region is too low for variable weight constraints to be integrated into any explicit operational restriction.



Figure 8: Survey of leading UAV-LMD industry leaders in UAV hardware empty weight, max payload weight and MTOW.

2.1.3 In-Air Vehicle Separation Restrictions

The notions of airspace structure and in-air separation exist to provide a priori separation and organization of aerial traffic in what is otherwise an unconstrained operating environment. This is particularly true for altitudes well above geological and urban structures. Thus, in-air separation is not a safety-related or operational challenge unique to UAV-LMD but to both manned and unmanned aviation more broadly. Beyond controlled airspace, aircraft separation services are not typically provided by ATC towers. Instead, aircraft operators are left to their own devices to remain “well clear” of other aerial vehicles and maintain an “acceptable” level of safety. The idea of “acceptable” level of safety is a complex conundrum, particularly

FAR Part 91 goes on to state that formation flight is possible if all pilots in command agree to the formation, with the only exception being if there are paid passengers on board any of the participating aircraft. But to translate these FAR Part 91 requirements into guidelines for manned aircraft pilots today, a mixture of rules are applied depending on cruise altitude. The first approach to self-separation is cruise altitude stratification based on flight direction. This often takes the shape of the quadrantal rule, which is enforced within the altitude range of 3000 ft. to FL240 (Ford, 1983). In the quadrantal rule, aircraft with headings between 000–089° are required to fly at odd altitudes in multiples of 1000 ft., whilst aircraft with headings 090–179° are constrained to odd altitudes in multiples of 1500 ft. Similarly, flights with headings between 180–269° must utilize even

in the aviation industry, but it typically comes down to rigorous simulations that certify that the probability of catastrophic disaster and human fatalities are similar to an equivalent probability in another domain in aviation or transport. The notion of “well clear”, on the other hand, stems from FAR Part 91 General Operating and Flight Rules, which states only two requirements to meet compliance:

- 91.111: “... not operate so close to another aircraft as to create a collision hazard”; (FAA § 91.111 Part 91, 2020)
- 91.113: “Vigilance shall be maintained ... so as to see and avoid other aircraft ... pilots shall alter course to pass well clear of other air traffic.” (FAA § 91.113 Part 91, 2020).

altitudes in multiples of 1000 ft., whilst flights with headings in the range of 270–359° are constrained to even altitudes in multiples of 1500 ft. This approach typically applies to aircraft flying under Instrument Flight Rules (IFR) above 2000 ft. mean sea level (MSL) or aircraft flying under Visual Flight Rules (VFR) above 3000 ft. MSL. With that said, all IFR flights must provide specific flight trajectories before take-off which may not precisely follow these altitude separation standards. For aircraft cruising above FL240 (which is a unit of aircraft altitude, or flight level, measured at standard air pressure and expressed in hundreds of ft.) a similar hemispheric rule is commonly used. This rule ensures that cruising aircraft above FL240 with travel directions in ranges of 000–089° and 090–179° are assigned to odd altitudes in multiples of 10, while cruising aircraft with head-

ings between 180–269° and 270–360° are constrained to even flight levels in multiples of 10 (Ford, 1983). Both airspace structure frameworks exist to lower conflict probability and thus decrease incidence probabilities and increase airspace capacity.

For low-altitude aircraft operations, however, self-separation via altitude stratification based on heading either: 1) has not been comprehensively defined and trialed; 2) is not currently well adopted, or 3) is not currently mandated as part of operational regulations. Instead, self-separation is predominantly maintained via longitudinal and latitudinal separation. One additional dimension to in-air vehicle separation that is relevant to low-altitude flight is that of repeating time intervals between sequential take-off and landing procedures. Both fixed-wing and rotary-wing (i.e., helicopters) aircraft generate strong wake vortices during take-off and landing maneuvers that emanate from the wing-or blade-tips. The kinetic energy contained in these vortices dissipates over the following minutes but, until then, can prove disruptive forces in the aerodynamics of following aircraft. But since the strength of such vortices decreases with the mass of the aircraft responsible, take-off and landing time intervals have not been commonly discussed in the context of UAV-LMD operations. However, if such UAVs are operated in an airfield with other much larger aircraft, such time delays will, indeed, have to be taken into account to ensure the UAVs do not enter potentially unstable flight dynamics.

A commonly cited method for installing low-altitude airspace structure is to simply duplicate the ground-level street network in the air

to serve as UAV “highways” (Thompson, 2019). This is a popular idea because urban street networks contain a great deal of positional information about the physical layout and geographical constraints of a city and its buildings. Furthermore, this could minimize the negative externalities that UAV-LMD are likely to impart on society – be it noise, privacy or trespass – just by being strictly situated over streets and highways. With regards to noise, not only would UAV-LMD noise pollution likely be masked by that from the road traffic below, but the public are likely more tolerant of noise emitted on streets because of its historic association with road-traffic and noise. With regards to privacy and trespass, since streets are, on the whole, public goods and assets, UAV-LMD can eschew the risks associated with private property on either side of street. This is to say that much of the information and benefits contained in urban street networks can be quickly assimilated into the low-altitude airspace structure with little overhead. With all its benefits, the notion of UAV “highways” has not yet been adopted in practice because of some key issues. First, such “highways” could well substantially reduce the efficient point-to-point travel advantages that UAV-LMD has over ground-based delivery modes. Thus, UAV-LMD industry players are actively push back against such regulation. Second, the aviation industry is unfamiliar with the notion of aerial “highways”, particularly true in low-altitude flight, since airspace structures until now have been built upon distinctions between VFR and IFR and the quadrantal and hemispheric rules. Third, such “highways” could constrict UAV-LMD operations to a narrow lateral and vertical band

of airspace and inadvertently increase conflict and collision probabilities. Such a narrow band of airspace may simply not be adequate to support expected UAV-LMD delivery volumes.

So although requirements for in-air separation are not well defined for low-altitude aircraft operations or uniquely defined for urban areas, they are currently commonly accepted in more traditional aviation domains to provide a safer and more fluid airspace. In high flight-density regions such as New York City, the FAA has worked with local regulators to define special flight rules and communication frequencies that go beyond FAR Part 91 and accepted airspace management frameworks to further minimize conflict probabilities (Federal Aviation Administration, 2022c). This report posits that in-air separation frameworks will either exist as accepted standards in low-density UAV-LMD regions or as special operating procedures, codified in regulation, in high-density UAV-LMD regions. But the shape that such frameworks take in both scenarios remains unclear. Because time-dependent separation during take-off and landing procedures is predominantly driven by safety concerns operating in wake vortices, such operating constraints are not considered key opera-

The specifics of such a stratification logic is not critical. This report, instead, seeks to highlight the importance of a protocol and its potential impact on UAV-LMD operations. Note that such an airspace structure does not address the collision risk when UAVs ascend into and descend from their allocated altitude strata to take-off or land. One approach is to analytically show that the probabilities of collision

tional constraints to UAV-LMD.

With regards to altitude stratification protocols, dynamic detection and avoidance algorithms that UAVs will likely leverage as fail-safe collision avoidance mechanisms are beyond the scope of this report. Their dynamism alone defines them as closer to a stochastic routing problem than a simple static operational routing model. Instead, this report puts forth a preliminary static altitude stratification protocol akin to the hemispheric or quadrantal rules for urban UAV-LMD operations. Based on the analyses of drone collision probabilities based on kinetic theory and interesting insights on how to strictly minimize collision probability in a dense urban area, this report puts forth the following altitude stratification logic, also depicted in Figure 9:

UAVs travel

- (a) due north ($315\text{-}045^\circ$) in the altitude range of 200-250 ft.;
- (b) due east ($045\text{-}135^\circ$) in the altitude range of 250-300 ft.;
- (c) due south ($135\text{-}225^\circ$) in the altitude range of 300-350 ft.; and
- (d) due west ($225\text{-}315^\circ$) in the altitude range of 350-400 ft.

based on expected UAV numbers meet an acceptable risk threshold, and not intervene with specific protocols (Doole et al., 2021). Another approach would be to perform take-off and landing procedures in conjunction with UTM systems (as they are today for the majority of larger manned aviation operations) to further minimize collision probabilities.



Figure 9: Graphic of proposed altitude stratification protocol for UAV-LMD.

Such a stratification protocol could also break down if geographical barriers do not permit UAVs to fly due north because of their allocated altitude range but do permit travel due east, south or west. One solution would be to strictly disallow UAVs beyond their allocated altitude strata with UAVs that want to fly due north having circumnavigate any geographical obstacle. Another solution could be to allow UAVs to travel beyond their allocated altitude strata but with safety contingencies such as a maximum time in a different altitude strata or a certain level of on-board collision avoidance capability. How such an altitude stratification protocol manifests in real-world UAV-LMD routes is shown below. Example no-fly zones and noise sensitive zones typically delineated for Boston, MA, are included for informational purposes.

2.1.4 Take-Off and Landing Considerations

Traditionally, manned aircraft that could be considered and regulated as low-altitude aircraft operations often spent the majority of their flight time at altitudes well above the prescribed minimum flight al-

titude and even well above low-altitude heights all together. During take-off and landing procedures, however, these aircraft operated in much closer proximity to urban structures and human populations below. Currently, take-off and landing procedures are regulated as exemptions to the rules that pertain to low-altitude flight. As discussed in Section 2.1.1, FAR §91.119 exempts aircraft that are performing take-off or landing maneuvers from the prescribed flight minimums (FAA § 91.119 Part 91, 2020). Pilots of these manned aircraft must adhere to procedures and standards that are publicly available and often part of the pre-flight airspace familiarization procedure for that particular airfield. Additionally, pilots are typically informed about local hazards and safety considerations for that particular airfield and nearby airfields. Take-off and landing operations at locations not designated as official airfields are often possible but likely subject to a different set of operational and regulatory constraints often set by local municipal and state regulators. These are typically designed to protect against the societal externalities (see Section 3) that landowners and local communities are impacted by. UAVs in-

involved in UAV-LMD are not only likely to be in close proximity to ground-based hazards during take-off and landing but also during their package delivery procedures and even in cruise flight considering their current altitude range restrictions. Thus, whilst much of this regulatory structure will likely also apply to UAVs involved in UAV-LMD, it is unclear if any additional constraints will emerge for UAV-LMD specifically. Even for manned aircraft, regulations

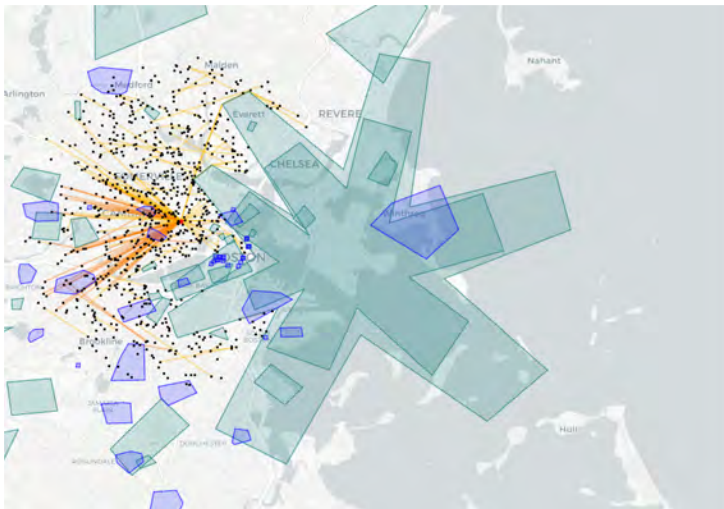
§S.2607.3.e.1 in the “Drone Integration and Zoning Act of 2019” empowers local and state regulators to regulate the “time, manner and place of operation” UAV operations. This power could well be exercised to reflect the needs and expectations of the community stakeholders involved. In this eventuality, this report expects take-off and landing procedures to also be regulated as to protect those same needs and expectations in a similar fashion, be it via maximum noise emissions standards, flight frequency caps or flight time-of-day restrictions. Thus, from the perspective of federal regulation, this report assumes there to be no additional take-off- and landing-specific regulations relevant for UAV-LMD. This report does not attempt to address the different potential eventualities that local and state regulators could enact via local take-off and landing constraints. Instead, this report assumes that, or preliminary UAV-LMD routing purposes, a simple heuristic for take-off and landing procedure would suffice: UAVs do not perform a shortened vertical take-off maneuver followed by an angled climb segment to cruise altitude. Instead, UAVs perform a single vertical take-off climb maneuver to their cruise altitude

around take-off and landing procedures for low-altitude aircraft are ill-defined at the federal level. Thus, this report posits that take-off and landing constraints for UAV-LMD will likely be more heavily dependent on local and state regulations rather than the FAA, and that the shape such constraints take will be highly dependent on the local stakeholders involved and their preferences.

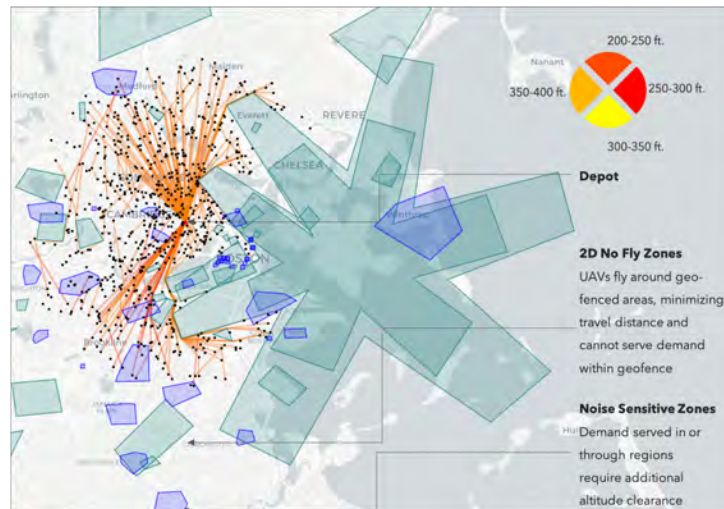
at which they transition to horizontal flight. This avoidance of an angled climb and descent is assumed for the UAVs’ landing maneuvers as well.

2.1.5 Flight Zoning Restrictions

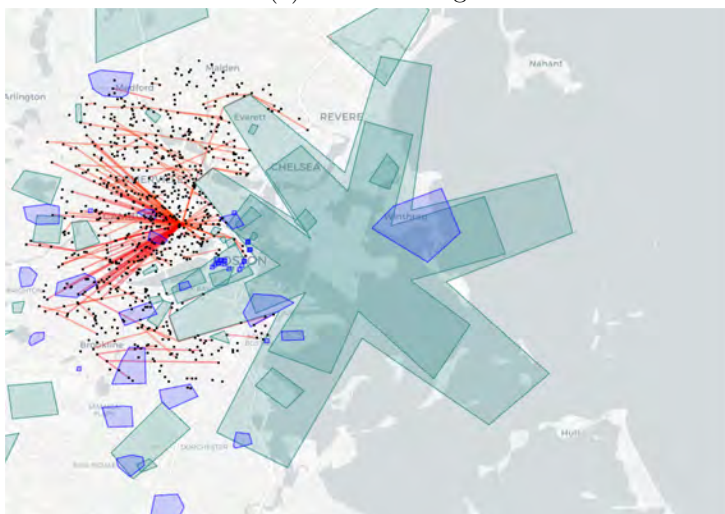
Today, UAV-LMD airspace restrictions and flight zoning is predominantly instituted by the FAA and are termed “No Drone Zones.” The FAA operates an online platform, B4UFLY, in partnership with ALoft, formally Kittyhawk, that informs UAV operators where they are permitted and not permitted to fly. It also guides users through the process of submitting for automatic authorization to fly in non-controlled airspace regions but does not facilitate this process for controlled airspace regions, known as the FAA’s Low Altitude Authorization and Notification Capability (LAANC), since such authorization must be granted by the ATC unit of the relevant airport or airfield. The types of “No Drone Zones” that currently exist are (Federal Aviation Administration, 2022b):



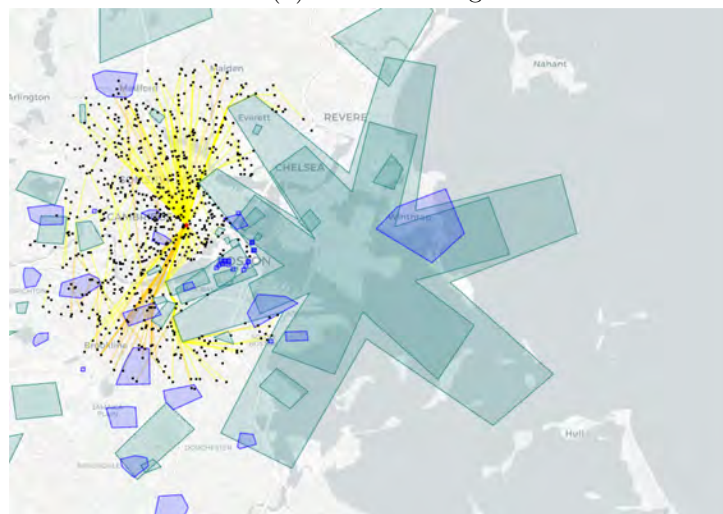
(a) West heading



(b) North heading



(c) East heading



(d) South heading

Figure 10: Traversed UAV routes with altitude stratification protocol implemented in UAV-LMD routing optimization logic, Boston, MA.

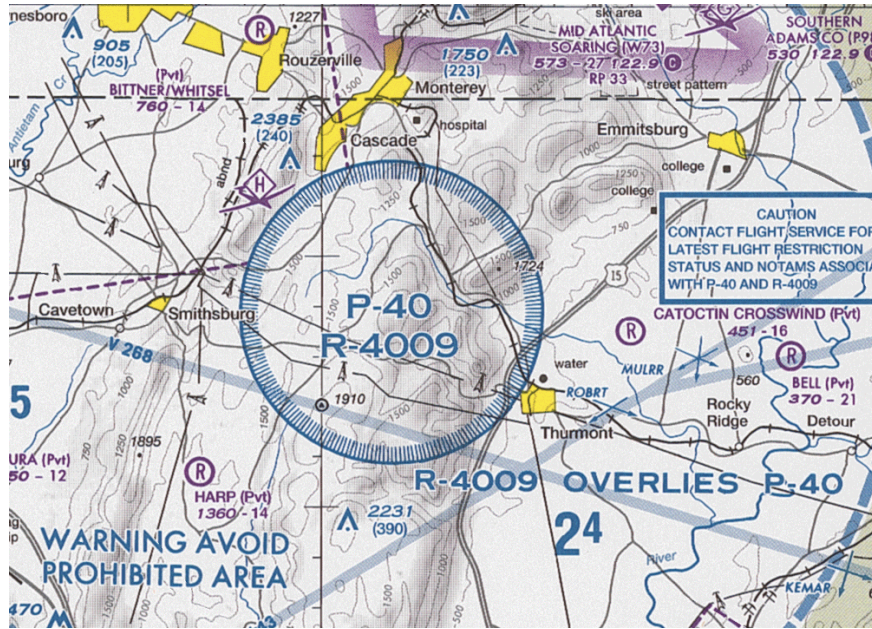
- Prohibited airspace: these regions of airspace fully prohibit aerial operations, both manned and unmanned, and are typically time-independent. Such areas are established under national welfare interests. Examples of such areas are Thurmont, MD, the site of Presidential retreat Camp David or Naval Submarine Base Kings Bay, GA. These are typically clearly depicted and publicized on aeronautical charts and also feature on the B4UFLY application. Examples of such charts are Figures 11a-??.
- Restricted airspace: regions of airspace through which any civilian aviation traffic, both manned and unmanned, are not permitted but may only be exercised during certain “active” times. These regions often contain unusual and hazardous operations such as missile launch sites, air combat training, military bases.
- Local restrictions: in some locations, UAV take-off and landing operations are restricted by state, local, territorial or tribal regulatory agencies. Note that these operators have the power to specifically restrict take-off and landing operations but currently do not possess the power to restrict flight in the airspace above the identified area. This will be discussed in further detail in Section 2.2. Additionally, national, state and potentially municipal parks or prisons and detainment locations, sport stadiums, schools and hospitals also represent locations that are often capable of imposing zoning restrictions through various regulatory or advisory pathways. Whilst many of these locations are explicitly stated on public forums and informational pages, it can often be unclear whether a specific location is, indeed, restricted airspace mandated through regulation or rather through a flight zoning advisory memorandum.
- Temporary flight restrictions: these are specific areas for which UAV operations are not permitted for a limited period of time with pre-approved certification by the FAA. Examples of such restrictions may include sporting events, presidential movements, natural disasters or security-sensitive areas designated by other federal agencies. Such restrictions can include geo-fencing, altitude minimums and maximums, time and the types of operations that are permitted.

In addition to “No Drone Zones” and the various levels of zoning restrictions mentioned above, there are likely to be additional context-specific restrictions based on the agreements the UAV-LMD operator has reached with any ATC operators of airfields that have jurisdiction of the region of operation. For example, an UAV-LMD operator in Boston, MA, will likely have had to gain an operations waiver from both the FAA and work directly with Boston Logan International

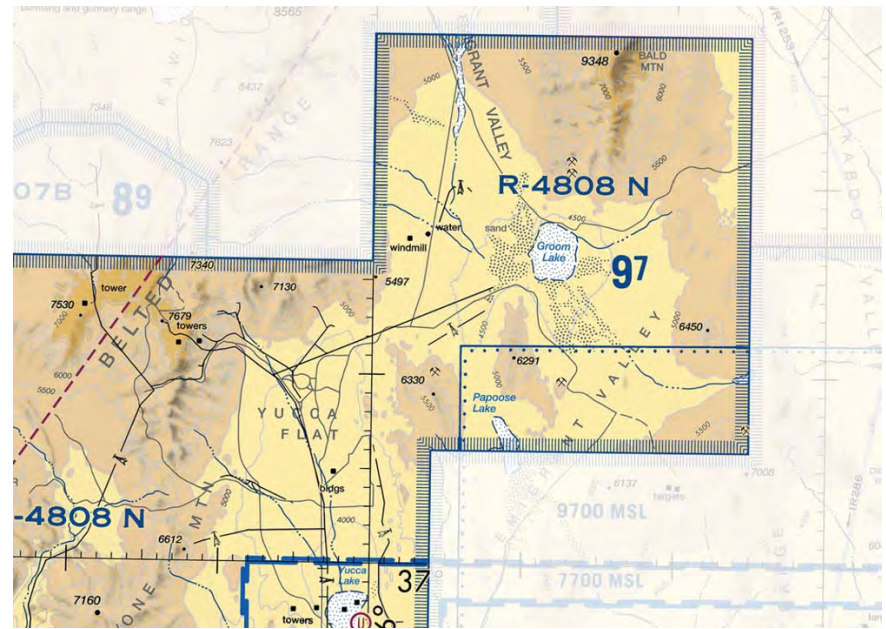
Airport to establish additional zoning and time-dependent zoning restrictions based on any emergency take-off or landing events centered at Logan. So whilst, today, UAV-LMD operators may be totally barred from the Class B airspace imposed by Boston Logan unless granted a waiver, closer collaboration between operator and Boston Logan could mean that UAV-LMD has to simply avoid a tighter geofence around Boston Logan and the projected take-off and approach

flight paths into its six runways. UAV original equipment manufacturer (OEM) DJI actually provides an informational flight zoning service worldwide for its customers through which they advise to avoid high-altitude flight in Boston Logan’s published approach flight paths (DJI, 2022). This report posits that many of the locations

that are now only considered “restricted airspace” and “local restriction” locations above in certain regions across the U.S. will become more commonly enforced across the country, these locations being: stadiums and sporting locations, prisons and detainment locations, schools, national, state and certain municipal parks and hospitals.



(a) Prohibited airspace at Camp David, MD.



(b) Restricted airspace at Yucca Flat nuclear test site, AZ.

Figure 11: FAA-mandated airspace restriction examples.

Currently “No Drone Zones” are exclusively instituted by the FAA with state and local regulators only permitted to enact pseudo-zoning restrictions via take-off and landing operations constraints. The trade-offs of federal versus local regulation particularly with regards

to UAV-LMD zoning restrictions will be discussed in more detail in Section 2.2. Additionally, the notion and importance of time-dependent regulation, which may be relevant to take-off and landing operational constraints, will be discussed in Section 2.2.

2.1.6 Safety-Related Procedures and Precautions

General aviation safety themes. When it comes to precautionary safety measures, the aviation industry is steeped in history and regulation and typically receives a substantial amount of public scrutiny around safety practices and track records. In 1926 to 1927, there were a total of 24 fatal commercial aircraft accidents amounting to an accident rate of 1 for every 1 million miles flown. Scaled to today's flight hours, this would equate to 7000 fatal incidents per year. Today's actual rate (during the period of 2002 to 2011 assumed to be comparable to today's safety record) is 0.6 fatal incidents per

Safety hazards.

- Weather: from lightning strikes to ice and snow, aircraft are designed to minimize the risk of catastrophic system failure in these eventualities. For instance, aircraft are covered in a metal "skin" that offer the first line of protection from lightning strike but they also contain a second metal mesh "skin" that conducts electricity around the outside of the vessel, minimizing risk of voltage shocks to those onboard and onboard flight controls and wiring. Of course, flight trajectory planning to minimize lightning strike risk is also a critical precautionary strategy. Pre-flight de-icing procedures and built-in de-icing technologies on aircraft wings and engines intakes also exist.
- Component or structural failures: whilst there are a number of precautionary measures (discussed below) taken to minimize the risk of foreign object damage, excessive load cycling and material fatigue or manufacturing defects, aircraft are designed with numerous redundancies and flight envelope buffers to mitigate catastrophic engineering failures.
- Human factors: pilot error is often cited as the most common factor in aviation accidents. Typical causes of human error are pilot fatigue, communication failures or incompetence, all of which are combated via training procedures and certification processes such as rigorous pilot licensing, Crew Resource Management procedures, rules and regulations around protecting crew health and alertness and a technological push to flight autonomy and augmenting onboard decision making processes.

1 million miles or a 99.9% decrease (CAA, 2013). Whilst aviation safety is an incredibly detailed and complex topic, there is value in exploring some of the overarching themes that aviation safety is centered around. This section does not seek to explore the broad topic that is how UAV-LMD safety precautions will likely evolve over the coming years. Instead, this section aims to simply filter the safety precautions taken for general manned aircraft operations for those constraints potentially relevant for UAV-LMD and supplement these constraints with any UAV-specific safety constraints that could emerge. Oster Jr et al. (2013) offers an accessible summary of key aviation safety themes.

- Runway safety: Runway incidents typically fall within the following incident types: runway excursion (the aircraft exits the runway incorrectly), overrun (runway overshoot), incursion (a foreign object incorrectly enters the runway), and confusion (miscommunications or misunderstandings during take-off or landing procedures).

Accident survivability.

- Airport design: ground-based infrastructure design can have a large impact on aviation safety, also often dictated around the types of aircraft the airport was designed around (propellers versus jets). Runway buffers and technologies (one example being engineered materials arrestor systems), security protocols and onsite emergency services all serve to minimize the likelihood of accidents becoming fatal.
- Emergency response procedures: from onboard evacuation procedures and associated technologies to aircraft design centered around frictionless evacuation to onboard and airport-based emergency response equipment and materials, the aviation industry and aircraft design is designed around worst-case emergency response scenarios.

Precautionary measures.

- Certification: is the means through which regulators, namely the FAA, manage risk through safety assurance providing a level of confidence that a proposed product or operation will meet the safety expectations set by the regulator and the society that regulator is representing. Certification is pervasive in the aviation industry and can be categorized in the following buckets:
 - Airmen: pilot, mechanic and crew typically fall in this category;
 - Aircraft: airworthiness (whether a particular aircraft meets safety standards as is fit to fly) and type certificates (whether a particular kind of aircraft is approved to fly) based on aircraft design and testing. Special airworthiness also falls in this category and is often used to cover experimental aircraft to promote research & development (R&D), but with severely limited scope for operations.
 - Production: pertains to a manufacturer's approval to manufacture the vehicle or vehicle components that fall under an approved vehicle type certificate, based on the manufacturers personnel, equipment, quality control and product testing.
 - Air carrier: typically covers airline and airline operator, pilot and training school, repair station and maintenance training certification.
 - Airport: certifies airports for their ability to serve scheduled and unscheduled aircraft with all necessary safety equipment, procedures, personnel, training and infrastructure available.

- Information and communication: information overload, pronunciation issues and communicative misunderstandings are key reasons behind aviation incidents. ATC providers, pilots and crew are often required to speak several languages as a redundancy to the de-facto worldwide aviation language, English, for which trainees must pass examinations for to receive their licenses. Furthermore, a host of standardized phrases and communication protocols used across airports and countries are adopted to minimize the risk of misunderstandings.
- Pre-flight checks: these are typically a list of tasks that should be performed by pilots and crew prior to take-off or after the aircraft docks at its final landing gate to improve flight safety by ensuring no important tasks are forgotten or overlooked. Pre-flight checks also serve to identify any damage or material fatigue that might have accrued during recent flights but between larger maintenance overhaul schedules that could compromise performance in an upcoming flight.
- Aircraft maintenance: because of the often extreme performance routines that aircraft undergo and the natural cycling of aircraft operations (repeated take-off, climb, cruise and landing operations), the components and materials on the aircraft typically undergo wear-and-tear and material fatigue. Extensive documentation, protocols and regulations exist to ensure aircraft maintenance is performed comprehensively and to an acceptable standard regardless of where it is performed and by whom. Maintenance licensing also serves this purpose. Aircraft design can also be significantly guided around maintainability.

The UAV-LMD perspective. Much of these high-level safety priorities has been and will need to continue to be translated into FAR Part 107, FAR Part 135 and any additional regulatory frameworks in the coming years to ensure the safety expectations of the stakeholders involved are met, one key stakeholder being the urban communities in which UAV-LMD will likely operate. However, whilst many of these safety precautions will necessarily be translated over to UAV-LMD before substantial commercial operations could commence, it is beyond the purview of this report to extrapolate how these best practices in commercial manned aviation could look in UAV-specific regulation. This section addresses only those safety precautions considered directly relevant to UAV-LMD operations. Safety hazards,

for instance, typically refer to factors extrinsic to the operation of the UAV itself such as weather, human factors, take-off and landing safety and vehicle component failures. Whilst component and structural failures could well be related to how a UAV is operated, it is more likely to a manufacturing default or material failure. Thus, this report eschews conversations around safety hazards. Accident survivability also falls into this category of safety precautions that lie outside of the day-to-day operations of UAV-LMD.

Certification, particularly from the perspective of manufacturing, materials testing, operational fatigue and degradation and maintenance and standardization of personnel training, is pivotal to ensure a certain level of safety is met across UAV-LMD operations and it

remains a clear gap in current regulatory frameworks for UAV-LMD. But however pivotal such certification is to UAV-LMD safety, this report is only concerned with regulation that directly pertains to operations. This also applies to the information and communication protocols currently standard in manned aviation. Much of this is already captured in FAR Part 107 and will not be discussed in more detail here. One dimension of precautionary measures that could emerge as an operational constraint, however, is that pertaining to pre-flight checks and post-flight inspections. This is because pre-flight checks are, indeed, operational constraints that current commercial air-freight and airlines contend with as they strive to minimize time that the aircraft is grounded, i.e. airport turn-around times. This section begins to analyze current FAR Part 107 pre-flight

check requirements for UAVs and supplements this with additional pre-flight check requirements from current manned aircraft operations that this report suspects may be appended to current requirements as UAV-LMD continues to scale. Future UAV-LMD operators will likely leverage other standard pre-flight procedures such as the personal/pilot, aircraft, environment, and external pressures (PAVE) and illness, medication, stress, alcohol, fatigue, emotion (IMSAFE) checklists.

FAR Part 107 §107.49 “Preflight familiarization, inspection, and actions for aircraft operation” currently stipulates the following with additional additional guidance provided through an Advisory Circular 107-2A on §107.49:

- (a) “Assess the operating environment, considering risks to persons and property in the immediate vicinity both on the surface and in the air. This assessment must include:
 - 1) Local weather conditions;
 - 2) Local airspace and any flight restrictions;
 - 3) The location of persons and property on the surface; and
 - 4) Other ground hazards.
- (b) Ensure that all persons directly participating in the small unmanned aircraft operation are informed about the operating conditions, emergency procedures, contingency procedures, roles and responsibilities, and potential hazards;
- (c) Ensure that all control links between ground control station and the small unmanned aircraft are working properly;
- (d) If the small unmanned aircraft is powered, ensure that there is enough available power for the small unmanned aircraft system to operate for the intended operational time;
- (e) Ensure that any object attached or carried by the small unmanned aircraft is secure and does not adversely affect the flight characteristics or controllability of the aircraft; and

- (f) If the operation will be conducted over human beings under subpart D of this part, ensure that the aircraft meets the requirements of §107.110, §107.120(a), §107.130(a), or §107.140, as applicable.” (FAA § 107.49 Part 107, 2020a).

Advisory Circular 107-2A on §107.49 goes on to assert:

7.3: “Pursuant to the requirements of §107.49 ... the remote PIC must inspect the small UAS to ensure that it is in a condition for safe operation prior to each flight. This inspection includes examining the small UAS for equipment damage or malfunction(s). This preflight inspection should be conducted in accordance with the small UAS manufacturer’s inspection procedures when available ... and/or an inspection procedure developed by the small UAS owner or operator.” (FAA § 107.49 Part 107, 2020b).

and details specific pre-flight inspection items for UAVs in §7.3.4:

1. “Visual condition inspection of the small UAS components;
2. Airframe structure (including undercarriage), all flight control surfaces, and linkages;
3. Registration markings, for proper display and legibility;
4. Moveable control surface(s), including airframe attachment point(s);
5. Servo motor(s), including attachment point(s);
6. Propulsion system, including powerplant(s), propeller(s), rotor(s), ducted fan(s), etc.;
7. Check fuel for correct type and quantity;
8. Check that any equipment, such as a camera, is securely attached;
9. Check that control link connectivity is established between the aircraft and the control station (CS);
10. Verify communication with small unmanned aircraft and that the small UAS has acquired GPS location from the minimum number of satellites specified by the manufacturer;
11. Verify all systems (e.g., aircraft and control unit) have an adequate power supply for the intended operation and are functioning properly;
12. Verify correct indications from avionics, including control link transceiver, communication/navigation equipment, and antenna(s);
13. Display panel, if used, is functioning properly;
14. Check ground support equipment, including takeoff and landing systems, for proper operation;
15. Verify adequate communication between CS and small unmanned aircraft exists; check to ensure the small UAS has acquired GPS location from the minimum number of satellites specified by the manufacturer;

16. Check for correct movement of control surfaces using the CS;
17. Check flight termination system, if applicable;
18. Check that the anti-collision light is functioning (if operating during civil twilight and night);
19. Calibrate small UAS compass prior to any flight;
20. Verify controller operation for heading and altitude;
21. Start the small UAS propellers to inspect for any imbalance or irregular operation;
22. At a controlled low altitude, fly within range of any interference and recheck all controls and stability; and
23. Check battery levels for the aircraft and CS.”

Between FAR Part 107 and the Advisory Circular, the FAA has provided ample material for operators to build upon and for this report to postulate how pre-flight checks will be integrated into daily operations. However, the FAR Part 107 pre-flight check regime detailed above would be required before every UAV flight and, thus, may strike the reader as stringent and costly both in time-delay and labor. UAV operators can also expect to be required to perform periodic maintenance checks as is required for commercial aircraft. On top of the standard pre-flight check, commercial aircraft undergo a

series of more involved maintenance checks termed line-, A-, B-, C-, and D- checks which are done on a periodic basis measured by total flight hours or total number of flight cycling since the last check of the same type (National Aviation Academy, 2020). Whilst flight cycling may seem an arbitrary unit of maintenance measure, it is deemed important, particularly in commercial aircraft, to prevent excessive material cycling and fatigue. However, in both Part 107 and the Advisory Circular 107-2A, the FAA has not detailed specific maintenance schedules for UAVs but only stipulates:

7.2: “[S]cheduled and unscheduled overhaul, repair, inspection, modification, replacement, and system software upgrades ... necessary for flight. ... operator should maintain ... in accordance with manufacturer’s instructions ... or, if one is not provided, ... may choose to develop one.”

7.2.1: “The manufacturer may identify components of the small UAS that should undergo scheduled periodic maintenance or replacement based on time-in-service limits (such as flight hours, cycles, and/or the calendar-days). Operators should adhere to the manufacturer’s recommended schedule for such maintenance.”

7.2.1.1: “If the small UAS manufacturer or component manufacturer does not provide scheduled maintenance instructions, the operator should establish a scheduled maintenance protocol.”

The FAA’s maintenance guidelines, thus, do not provide specific time-limits for maintenance and defer to 1) UAV OEMs to provide suggested maintenance schedules; and 2) UAV operators to supplement or define their own maintenance schedules to maintain safe operations. This report, thus, posits that the key drivers that operators will respond to that will guide maintenance check time limits

2.2 Miscellaneous Regulatory Issues and Areas of Uncertainty

This section is a qualitative survey of areas of regulatory uncertainty that remain unresolved in current regulatory frameworks, literature and discussions. A recent techno-ethical review of commercial UAV literature quoted the most cited concerns for commercial UAV deployment were the safety of ground-based bystanders and legal pathways that espouse personal protection legal claims. Whilst these concerns are well documented both in the literature and this report, public concern will continue to guide how the relevant regulation evolves. Whilst much of the discussion in this section is not directly relevant for this report’s modeling approach, unresolved issues can provide insight into the evolution and trajectory of UAV-LMD regulation in the coming years.

2.2.1 The Time Component of Regulation

To increase the efficiency and applicability of regulation, regulators could leverage time-dependent regulation to a greater degree than currently so in FAR Part 107 and 135 (Rule, 2016). UAV-LMD

will likely be 1) operators seeking to minimize the time-delay, labor cost and equipment cost associated with more frequent maintenance checks; 2) ad-hoc FAA inspections to ensure maintenance compliance; and 3) consumer, societal or internal pressure to maintain high safety standard or reputation.

operations are likely to be short-lived interferences that repeat multiple times a day. Thus, they are also more likely able to adapt to time-dependent regulation. Furthermore, the specific time of day or year can significantly alter on how UAV operations are perceived by bystanders. For example, residential communities may prioritize privacy, particularly in the afternoon hours on the weekends during the summer months when their outdoor back yards and swimming pools are more frequently used. UAV-LMD operations could well be considered more disruptive, annoying and intrusive at these times compared to afternoon hours on the weekends during the winter months. Thus, whilst currently only seen in FAA issued Temporary Flight Restrictions (TFRs), time-specific operational constraints via localized regulatory pathways could become common-place.

2.2.2 Local and State vs. Federal Regulatory Divergence

The balance of regulatory authority between local versus federal regulators is an issue that exists in legislation beyond just UAV-LMD;

however, UAV-LMD is distinct in the aviation sector in that it is very closely integrated with local geographies and communities. Historically, the regulatory authority in this sector has generally been more heavily skewed towards the federal regulators (Rupprecht). Indeed, the FAA is well suited to address many of the emerging regulatory challenges associated with UAV-LMD: flight restrictions around otherwise federally regulated entities such as airports, military facilities, national borders and other manned aerial traffic (Mark Connot, 2016). National UAV registration and tracking programs also enable a level of traceability, standardization and identification for law enforcement officials. Finally, uniform federal certification addressing manufacturing, maintenance and operational safety provides a nation-wide industry standard for UAV aircraft design and sales across the country.

However, until now, the FAA's roll-out of pertinent regulation in response to the rapid appearance of commercial and private UAV deployment has been widely criticized as slow and insufficient to protect against the localized externalities imparted by UAV operations. On the other hand, local and state regulators are commonly thought quicker-to-legislate and better suited to draft regulation more closely aligned with local community sentiments and requirements. The FAA currently claims preemptive regulatory authority over the majority of these local issues as well. Whilst the FAA allows some flexibility when it comes to creating and implementing UAV regulation at local levels, it advises states and municipalities not to stray too far away from their operational guidelines. However, in many con-

texts, their ability to enact standardized regulation at the national level has little to no bearing on addressing these localized concerns. With more and more states and municipalities drafting their own set of UAV usage laws through alternative regulatory pathways such as personal protection law or laws that protect property rights, it is becoming increasingly apparent that gaps exist in the FAA's ability to protect the public. For example, in 2013, the Oregon state legislature passed a law providing landowners the right to legal action against individuals operating UAVs below 400 ft. above their property (Koebler, 2013). The law assumed that these were repeated UAV flights and the operator had been notified. So whilst not in direct contradiction to the altitude-minimum guidelines in the 'Drone Integration and Zoning Act of 2019', this highlights 1) the ability of local regulators to constraint UAV-LMD operations even without substantial aviation-specific regulatory authority, and 2) their willingness to take regulatory stances in direct conflict with federal regulators. Whilst local regulators may be better suited to translate the needs of local communities into regulatory frameworks, there is a trade-off between localized representation and the emergence of a "patch-work" of differing low-altitude regulatory frameworks (Rule, 2016). In this case, operators will incur a compliance cost of adjusting operations to each regional regulatory framework which could result in differing altitude, trajectory, speed, MTOW or operating time requirements. This report supports the need for increased local and state regulatory authority but with the keeping of this trade-off in mind for the economic feasibility of UAV-LMD operators.

The method of analysis that this report undertakes could well be informative for quantitatively measuring this trade-off: by varying levels of specific regulatory-specific operational constraints, a better understanding of UAV-LMD's sensitivity to specific constraints could be gleaned. This could inform along which dimensions local and federal regulators should be willing to concede authority with minimal impact on operations and which other dimensions more significantly harm an operator's ability to provide UAV-based service. Furthermore, by instituting varying intensities of constraints in different sub-regions of the same demand set, this model could provide insights into how harmful a patchwork of regulatory constraints would be to operations.

2.2.3 Localized Flight Zoning Restrictions

One of the greatest potential advantages for increase local regulatory authority is for a systematic tailoring of UAV no-fly zones and other localized flight restrictions specific to the needs and requirements of specific communities. Naturally, these needs will likely stem from the

personal protection expectations discussed in further detail in Section 3.1. Since these are needs that emerge out of local phenomena such as population demographics, expected background noise levels or familiarity with UAV technology, it is expected that these needs vary from neighborhood to neighborhood. Localized UAV flight zoning authority can enable the national low-altitude airspace account for such differences in the same way that land use zoning has served that function for nearly a century (Rule, 2016). Adjusting the flight restrictions based on the changing needs of the local community is also easier if regulated locally, especially if resistance to UAV-LMD begins to thaw and operators seek to serve that regional market.

This report posits, however, that continually changing flight zoning restrictions could represent a heavy drag on establishing stable UAV-LMD operations in a specific area because of the high up-front infrastructure, regulatory compliance, public acceptance and supply chain costs associated with establishing operations in that region. It remains unclear how local regulators will approach zoning restrictions, but local regulators adopting different methodologies is a possibility.

Societal Barriers



3 Societal Barriers

On February 15, 2015, President Obama issued a public memorandum titled “Promoting Economic Competitiveness While Safeguarding Privacy, Civil Rights, and Civil Liberties in Domestic Use of Unmanned Aircraft Systems” (The White House, 2015). In the memorandum, the administration asserted their expectation that the FAA account for privacy, security, and transparency while integrating UAVs into the NAS. This section dissects the potential for nega-

3.1 Personal Protection

Under the umbrella of personal protection, private individuals have the right to protect themselves and their property from the potentially harmful encroachment of others. These rights often, but not exclusively, manifest in legal claims such as trespassing, nuisance and invasion of privacy. This section will explore each of these claim types in turn and determine how relevant, if at all, are they to UAV-LMD operations.

3.1.1 Trespass

Trespass is typically defined as knowingly encroaching upon another person’s land or property without permission. The Second Restatement of Torts at §159 states that an aerial vehicle can be deemed trespassing if it “enters into the immediate reaches of the air space next to the land, and it interferes substantially with the [owners] use

tive societal externalities that would likely emerge from commercial UAV-LMD in urban environments at scale. This analysis is informed predominately by available literature pertaining to UAVs in urban areas and low-altitude aviation operations in the past. But the reader should note that much of this analysis is predictive and estimative since there are few societies that have, up to today, experienced UAV-LMD and document its set of longer-term negative externalities.

and enjoyment of his land” (Sugarman, 1991). The Second Restatement of Torts offers additional guidance for such cases by suggesting flights a) over 500 ft. are unlikely to be intrude into private airspace, b) flights under 50 ft. most likely are and c) flights at 150 ft. is circumstance dependent. And a strong trespassing case typically requires the vehicle’s intrusion to detract from the use and enjoyment of that private property.

Interestingly, in 2015 the FAA issued guidance which anticipated that states and cities will likely regulate UAV-LMD operations, but encouraged close consultation with the FAA prior to enacting laws. This is in line with broader separation of powers between state and federal regulation, particularly in local policing domains – including land use, zoning, privacy, trespass, and law enforcement operations. In 2018, however, the FAA modified this guidance by adding the

comment that state and local governments “are not permitted to regulate” UAV flight paths and altitudes.

“[F]lying at legal altitudes [that is, less than 400 feet] over another person’s property without permission or a warrant would reasonably be expected to constitute a trespass.” (Skorup, 2021).

Whilst the frameworks that will guide accusations of trespassing of low-altitude aerial vehicles remain vague, legal risk in this domain will likely force UAV-LMD operators to adapt their operations accordingly. UAV-LMD players may well establish direct trespass easements with their direct customers via terms and conditions contracts. But, of course, this does not capture those external to the transaction.

3.1.2 Nuisance

Nuisance is typically defined as the substantial and unreasonable interference of an individual’s enjoyment of their property through a thing or activity. Thus, it is likely to be more applicable to UAVs operating at low altitudes. Unlike trespassing, nuisance describes the type of harm that is inflicted and is not tied to property boundary or private airspace definitions. It is simply whether a thing or activity interferes with an individual’s enjoyment of their private property. Historically, in general aviation and commercial aircraft operation, nuisance claims have been submitted against owners of aircraft, airports. They are also typically based in state law or municipal regulation. There has been no guidance to date on if this will remain

in the hands of local regulators or be absorbed into federal aviation regulation.

Whilst UAV’s dust disturbance and noise footprints are typically smaller compared to helicopters and, thus, less likely to qualify as a nuisance claim, UAV-LMD will mean aerial pass-overs will be more frequent, operations will be more geographically dense and the average flight altitude will be lower because of repeated take-off and landing maneuvers. This report posits that whilst nuisance claims may be put forward against future UAV-LMD operations, operators themselves will not actively consider nuisance externalities with the precautions taken for the other societal externalities likely sufficient to also cover nuisance concerns.

3.1.3 Invasion of Privacy

Finally, invasion of privacy is defined as the unjustifiable intrusion into the personal life of another without consent. The Second Restatement of Torts at §652b asserts

“[o]ne who intentionally intrudes, physically or otherwise upon the solitude or seclusion of another or his private affairs or concerns, is subject to liability to the other for invasion of his privacy, if the intrusion would be highly offensive to a reasonable person.” (Sugarman, 1991).

In this light, the tort of invasion of privacy would not require the disclosing of information or images, just acquiring. Thus, the risk to UAVs is clear. UAVs will likely require an array of cameras and

sensors that will continuously monitor their surroundings to avoid collisions surrounding objects: buildings, trees, telephone and power lines, birds, and other aerial vehicles. This is particularly true if operations become near-autonomous.

As a back-stop to minimize legal exposure, UAV-LMD operators may be motivated to record, store and even review a UAV's flight mission footage. Should a UAV-LMD operator's employee have the right to review imagery or video captured by the UAV in flight? Should UAV operators be able to utilize the data a UAV collects for other commercial uses either internally as a commodity sold onto a third party? Just as Apple contends with pressure from security agencies and courts to disclose stored data on iPhones that could be used as evidence in legal proceedings, will UAV-LMD operators need to contend with such requests to share aerial data in similar contexts? Based on The Second Restatement of Torts, if an operator obtains data of a property that is deemed "highly offensive" by the courts, they would be liable to a claim for damages and/or an injunction for invasion of privacy.

In the U.S., March 15, 2017 signified the most resolute effort yet by Sen. E. Markey (D-Mass.) and Rep. P. Welch (D-Vt.) to introduce federal legislation to regulate UAVs. It actually took the form of a UAV privacy framework. Entitled the "Drone Privacy and Transparency Act of 2017", the proposed regulations suggested three methods to safeguard personal privacy threatened by UAVs: 1) require every person or firm seeking to use a UAV for commercial purposes to obtain pre-authorization to operate the UAV. This en-

tails providing certain information about where, when, and for what purposes the UAV will be flown, and whether it will collect, sell, or otherwise use personal information about any individuals; 2) require the FAA to publicly disclose this information on the Internet; and 3) ban any use of UAVs by law enforcement personnel without a warrant (Hall, 2017). Whilst it was never enacted, this piece of legislation signals to industry stakeholders the general intentions of Congress active members – the issues that face UAV-LMD extend far beyond the mere operational regulations.

3.1.4 Regulatory Pathways to Limit Personal Protection Externalities

Over the years, federal and state courts have handled many cases that challenged the legality of aerial footage of bystanders and private property being taken and stored by persons or companies. Such legal action typically questioned the admissibility of data collected in this way through filings for trespassing or personal nuisance. These cases often concluded supporting the aerial vehicle operator as long as they operated in accordance to FAA regulations rather than siding with or expanding on the rights of landowners or bystanders.

To what extent a landowner owns the airspace above their property has been a question with an unclear answer since the 1946 *United States v Causby* case, in which a chicken farmer sued the U.S. government for flying military planes at such low altitudes over his home that his chickens committed suicide out of agitation (Legal Information Institute). The U.S. Fourth Amendment protects citizens from

unreasonable search and seizure, particularly in areas where they can expect a certain level of privacy, namely their home or the curtilage of their home. But whilst one can expect privacy under the Fourth Amendment, objects, activities or statements that are exposed in plain view are not subject to the same privacy entitlements. This is why the Fourth Amendment has never required passers-by to shield their eyes when passing by a home (Brenner, 2005). This begs the question, which interpretation of the Fourth Amendment should UAVs be subject to?

Recent rulings in the U.S. can provide insights into how privacy concerns will be viewed in UAV-LMD operations. In *Florida v Riley* U.S. Supreme Court case, it was argued

“there is reason to believe that there is considerable public use of airspace at altitudes of 400 feet and above[.]” ((Supreme Court of United States, 1988))

Below 400 ft., this argument defending privacy encroachment weakens. Additionally, such issues are often heavily influenced by state and federal circuit law. With that said, as of today, FAA Part 135 air carriers are protected by the Airline Deregulation Act that prevents states from enforcing laws

“related to a price, route, or service of an air carrier.” (49 U.S.C. 41713, (United States Code, 2006 Edition, Supplement 5, Title 49 - Transportation, 2005))

The European Union (EU) more advanced when it comes to enacting data privacy regulations than the U.S. In 2016, the European Com-

mission and the Council of the European Union approved the General Data Protection Regulation (GDPR), instituted on 25 May, 2018 (Voigt and Von dem Bussche, 2017). One key facet of the GDPR is its purpose to “return control” to EU citizens over their personal data. One key dimension of the GDPR is that personal data is considered significant and “sensitive” to the private citizen if that data reveals information about that individual’s racial or ethnic origin, political opinions, religious or philosophical beliefs, trade-union membership, genetic makeup or bio-metric, health or sexual characteristics (Hoffmann and Prause, 2018). For UAV operators, the following excerpt applies:

“the controller shall be able to demonstrate that the data subject has consented to the processing of his or her personal data and the data subject shall have the right to withdraw his or her consent at any time.” Article 7, GDPR, (Voigt and Von dem Bussche, 2017)

The GDPR makes a distinction between the “data subject,” the “controller,” and the “processor” in data collection processes. In future UAV-LMD operations, the lines between these stakeholders will become blurred. UAVs will become more autonomous, the software engineers responsible will reside in remote locations and a number of UAV-LMD operators will operate across various locations with different integration and deployment strategies.

The perspective of UAV-LMD operators can be dissected into two viewpoints: 1) the three most common personal protection external-

ities discussed above are already captured in the various flight trajectory, operating time or minimum altitude constraints set forth by the FAA; or 2) it is the operator’s responsibility to minimize this risk and the snowball effect of worsening public relations with the public and, potentially, serviceable available market. To this end, this report seeks to explore along which dimensions a UAV-LMD operator would self-constrain operations to minimize such externalities:

- Flight trajectory constraints: actively avoid areas with community members that are likely sensitive to personal protection violations.
- Minimum altitude constraints: artificially set higher minimum altitude constraints either across all parts of a flight mission or over specific areas with community members that are likely sensitive to personal protection violations;
- Operating time constraints: self-regulate UAV-LMD operating times to more closely align with periods of the day during which any impacted community members are less likely to be impacted by UAV-LMD operations and avoid more personally sensitive periods of the day.

3.2 Noise

While urban communities tend to tolerate public safety helicopter flights (such as for medical or emergency operations) they have historically opposed frequent non-essential helicopter use in urban en-

Note that these societal constraints reflect community needs that are extremely local in scope, hinting at the broader discussion of how local versus federal regulatory authority will be balanced for UAV-LMD in the future. Also note that the operator’s tools to minimize personal protection externalities are predominantly the same as those present in FAA regulations, namely trajectory, altitude, and operating time constraints. Whilst this report could hypothesize as to whom these sensitive communities are, an analysis of which communities are more sensitive to these externalities has not been performed in literature and only briefly touched upon in industry-led efforts. A Virginia Tech report centered around public perspectives on Wing’s operation concludes that, amongst those surveyed, 87% “like the idea of drone [UAV] delivery” and 89% “would use the service” (Xu, 2017). This survey-based report does not detail the characteristics of those communities not in favor of Wing’s UAV-LMD operations and their specific qualms with the service. A survey-based approach to defining these sensitive communities is likely the most effective way to inform any society-driven operational constraints that operators who opt for self-regulation should adhere to.

vironments. This is, in part, because of the low frequency and clear community value of public sector helicopter use. Until now, only isolated municipal regulation has allowed small helicopter transporta-

tion services to take hold in cities like New York and Sao Paulo. Across other geographies, noise concern has often limited the scalability of any commercial helicopter urban aerial mobility operation, from flight frequency to route flexibility. But UAV-LMD will be just this: it will likely operate closer to bystanders on the ground, in a variety of geographic areas, at different times of the day and more frequently than current low-altitude aircraft operations.

3.2.1 Estimating Noise Impact

Estimating the impact of noise on a society is non-trivial from both a technical and social level. With that said, it is likely that the public will naturally benchmark the noise impact of UAV-LMD with

- Propeller blades: UAV propeller blades are the most notable broadband noise source. Their high blade tip generates significant downwash and associated lift disturbances that contribute to the unique tonal noise of the craft compared to traditional aircraft or helicopters.
- Payload: UAVs with heavier payloads generate more noise since more lift is required to counteract the added payload weight translating to high propeller speeds, additional air displacement, more turbulence and, thus, more noise.
- Forward flight: In a quadcopter configuration, forward flight is achieved by an imbalance in thrust vectors between the rear and front propeller disks, tipping the UAV in the direction of travel. This difference in rotational speeds can generate lift disturbances that increase noise production.
- Wind: Whilst wind can have a masking effect on UAV noise, it can also require the UAV to perform compensatory thrust maneuvers to maintain controlled flight. This results in additional irregular, high-pitched noises on top of the base noise profile.

Beyond this, however, estimating noise levels emitted from low-altitude commercial UAV-LMD operations is non-trivial from both

the only other commonly-occurring low-altitude aerial vehicle: helicopters. Compared to helicopters, UAVs emit a higher-pitched noise that may be perceived as incessant, since a UAV remains at low altitudes for longer periods than helicopters, which typically just perform brief pass-overs. It is this characteristic – their acoustic profile and operational pattern – that will dictate how UAVs are received in urban areas. The UAV-LMD industry is dominated by either quadcopter or lift+push vehicle UAV configurations. Both sport propellers with the latter differing in that forward flight is not powered by a thrust imbalance between front and back rotors but via a separate forward thrust system altogether. The dominant noise sources can be understood via Figures 12a and 12b:

a technical and social level. This is because little data and research exists that characterize the acoustic profile of UAVs or how the pub-

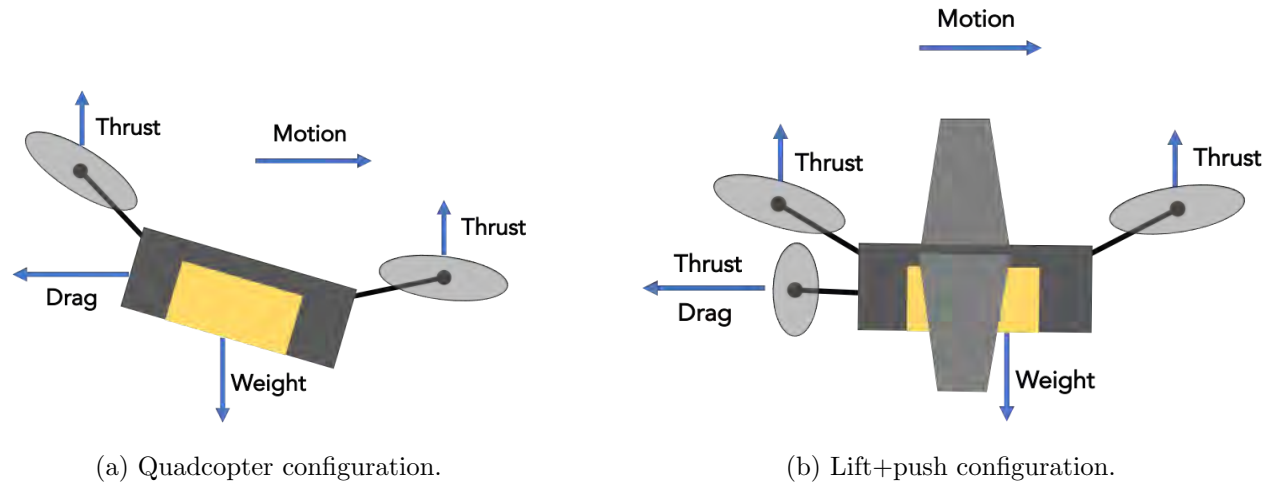


Figure 12: UAV force diagrams for differing UAV configurations.

lic would respond to such frequent noise disturbances. Furthermore, UAVs are likely to undergo substantial design adjustments as firms learn more about their demand base, operational limitations and regulatory constraints. But whilst analyzing UAV noise pollution on a quantitative level may be a difficult and, potentially, futile exercise, there are a variety of qualitative insights one can make to guide future regulatory and commercial decisions.

For one, it is not precisely the amount of noise pollution that matters but rather its annoyance factor. This comprises of the pitch, frequency, length of time and variability of the noise that matters. Furthermore, whilst considering the acoustic profile of a single UAV is important, the fleet noise profile over an extended time period is what bystanders take note of. Thus, frequency of UAV-LMD operations in a specific area also drives the annoyance factor. UAV-LMD network

design will likely play a pivotal part in municipal and commercial strategy to minimizing the negative externalities of UAV noise pollution. For example, some research suggests that a highly decentralized launch and retrieval network would reduce the overall noise footprint since the UAVs would spend less time in the air and travel shorter distances to their destinations (Lohn, 2017).

3.2.2 Regulatory pathways to limit noise externalities

The FAA has historically defined noise regulations in the NAS although local and state regulators do have a non-binding say in how their community noise standards are define. With that said, there are numerous examples of where aircraft or helicopter operations were curtailed or prohibited altogether because stakeholders objected to the aircraft noise pollution. One example is that of low-flying heli-

copters in Los Angeles prompting California representatives to push Congress to, in turn, push the FAA to draft new helicopter noise regulations and ultimately resulting in the Los Angeles Residential Helicopter Noise Relief Act of 2013 (Rep. Schiff, 2013). Whilst the Act did not strictly prohibit low-altitude helicopter operations outright, it provided voluntary measures for operators in the Los Angeles region to reduce noise.

Historically, larger manned aircraft and helicopter noise emissions are curtailed via airfield-specific operational constraints. For example, specific airports would limit operations that 1) fly in a certain direction over especially sensitive communities; 2) occur in noise-sensitive times (most commonly late at night and early morning hours); and

“(...) the FAA lacks sufficient evidence at this time to justify imposing operating noise limits on (...) UASs” (Federal Aviation Administration, 2021).

Part 107 does currently limit noise emissions, however, through two pathways: 1) it constrains the MTOW of UAVs certified under PART 107 to 55 lbs.; and 2) commercial UAVs are not permitted to fly over people not directly involved in the UAV’s operation. However, such constraining flight trajectories are changing with FAR Part 135 exceptions being granted to UAV-LMD operators. So whilst there does

3) the total number of take-off and landing maneuvers performed per unit time of operation. This is effective since such aircraft and helicopters are most noise-polluting when performing these low-altitude take-off and landing maneuvers but not necessarily during climb, descent or cruise flight regimes. But since UAVs in UAV-LMD are expected to operate at low-altitudes for the majority of a flight mission, this report expects noise constraints to extend beyond just take-off and landing procedures. With that said, take-off and landing locations will naturally increase flight density as UAVs will necessarily originate and finish their missions at that location. Looking specifically at FAR Part 107, it currently only quotes noise as a potential operational issue but concludes the following:

not yet exist a comprehensive set of UAV noise emissions standards either for individual UAVs or a fleet of commercial UAVs, there are some high-level approaches to minimizing UAV-LMD noise emissions that have been discussed in literature that would emerge in future FAA regulation:

- Technological: FAA regulation or public pressure can incentivize UAV OEMs to explore engineering solutions to noise emissions mitigation such as improved propeller designs, increased distributed propulsion or vibration and acoustics redesign. Such regulation can be both binding or voluntary with the latter more commonly seen in advisory circulars in historical noise mitigation efforts.
- Operating constraints: The FAA frequently institutes TFRs around special public- or other noise sensitive-events that prohibit flight over these areas either during specific times, at certain altitudes or with maximum MTOWs. Specific helicopter routes, airport transition

routes and VFR highways for reduce broad-based noise pollution by aggregating flights over sparsely populated areas or areas less sensitive to noise such as industrial parks or highways. Finally, the FAA enables airports to alter low-altitude approach and departure paths for noise-mitigation purposes through the FAA Airport Noise Program, through which pilots can be asked to adhere to specific noise emission guidelines. Aside from specific mitigation strategies, acoustic noise mapping pertaining to UAV-LMD is a field being heavily researched as a tool to combat noise pollution. Such a model combines a representative noise model for the UAV type and configuration in question, a translational scaling of a single UAV to a fleet of UAVs operating over the course of a time period, an understanding how such noise emissions propagates in the surrounding environment capturing factors such as the weather, exogenous noise polluters, and any noise muting characteristics. Such a model would be valuable to UAV-LMD stakeholders, be it regulators, operators or the public, since it provides a set of measurable metrics for noise emissions given differing operating circumstances against which regulations, operations and public expectations can be tuned. Thus, acoustic mapping would be an enabler of other noise mitigation solutions.

Whilst it remains unclear which of the two noise mitigation approaches are being more heavily pursued by the FAA and UAV-LMD industry players, this report leverages existing operations-based noise mitigation strategies for urban helicopter operations as a foundation for the UAV-LMD industry:

- cruise at higher altitudes;
- steeper take-off and landing procedures to minimize total time spent at low-altitudes;
- minimize specific noise emission profiles that are considered highly noticeable, penetrating or annoying. One example for helicopters is impulsive noise generation which is the loud repeated beating noise helicopters generate often when cruising at high speeds, also commonly referred to as “blade slap”; and
- avoid noise sensitive areas via detailed flight trajectory planning.

This report posits that all of these noise mitigation approaches are likely to feature in operator’s routing algorithms. In this way, this report assumes that UAV-LMD operators introduce self-imposed constraints to minimize noise externalities with additional minimum altitude restrictions in addition to minimum altitude constraints that emerge from UAV regulation.

This report also assumes additional drone zoning restrictions around locations that are likely to be noise-sensitive. With that said, there are many factors that dictate what defines a noise-sensitive area. In literature, some methodologies collect key geographic features and characteristics and leverage predictive models trained on submitted noise complaint data to measure noise sensitivity. Other methods rely on surveys to gauge noise sensitivity in place of noise complaint metrics. Some examples of geographic features are: population density, age, race and ethnic demographic spreads or land zoning types or proximity to other noise-pollution sources. With this said, delv-

ing into the details of noise sensitivity science is beyond the scope of this report. This report leverages the 2016 Greater Boston Noise Report and, specifically, the Neighborhood Sound Annoyance Lev-

3.3 Environmental Concerns

Unrelenting growth of the last-mile industry has taken its toll on local urban and global environments alike due to an ever increasing number of trucks required to fulfill demand and the fuel consumption and emissions associated with operations. The World Economic Forum study forecasts a 36% rise in the number of delivery vehicles in the world's top 100 cities by 2030, leading to an emissions increase of over 30% (Deloison et al., 2020). UAV-LMD excites many industry firms because of its potential to transport goods in a fraction of cost, time, and energy of today's methods. The majority of UAVs consume electricity and, thus, have no emissions when compared to a ground-based fuel-consuming truck at the tailpipe. But, the environmental friendliness of UAVs depends on factors that extend past the tailpipe and might be offset by: a) the UAV configuration, b) the size and weight of the cargo, c) the potentially longer linehaul distances they incur to fulfill a set of demand given their limited payload and battery capacities, d) the additional warehouses or charging stations required to extend their limited flight ranges, e) the carbon intensity of different upstream power generation systems, and f) the economic- or energy- competitiveness of alternative-fuel vehicles (e.g., electric and natural gas trucks). Furthermore, several studies point towards

els Map, shown in Figure 13, as an example to show how one could discern regions in the Greater Boston Area that will likely be more noise-sensitive to UAV-LMD (Walker et al., 2016).

a lack of scientific evidence of the environmental benefits of UAV-LMD as compared to existing modes of transport (Kellermann et al., 2020; Park et al., 2018; Stolaroff et al., 2018).

In UAV-LMD, emissions savings generally stem from the reduction of deploying under-utilized ground-based vehicles rather than fully replacing traditional ground-based vehicles (Chiang et al., 2019). This is particularly relevant in rural areas where distances traversed by ground-based vehicles are longer than by an aerial UAV and demand is not easily consolidated into single vehicles. Thus, it is not fair to compare UAV-LMD and traditional delivery vehicles on a one-to-one basis but rather measure by how much do the total fulfillment network emissions drop due to an introduction of UAV-LMD as part of the fulfillment mix. For example, UAV-LMD could have a net-positive effect on fulfillment network emissions if specific routes that, if performed by traditional ground-based modes, are mired in significant ground-based congestion, long and indirect road network routes (such as around large geological features or bodies of water) or across challenging terrain like steep gradients. Re-allocating many of these specific delivery routes to UAV-LMD could increase the overall sustainability of the entire fulfillment system.

Neighborhood Sound Annoyance Levels

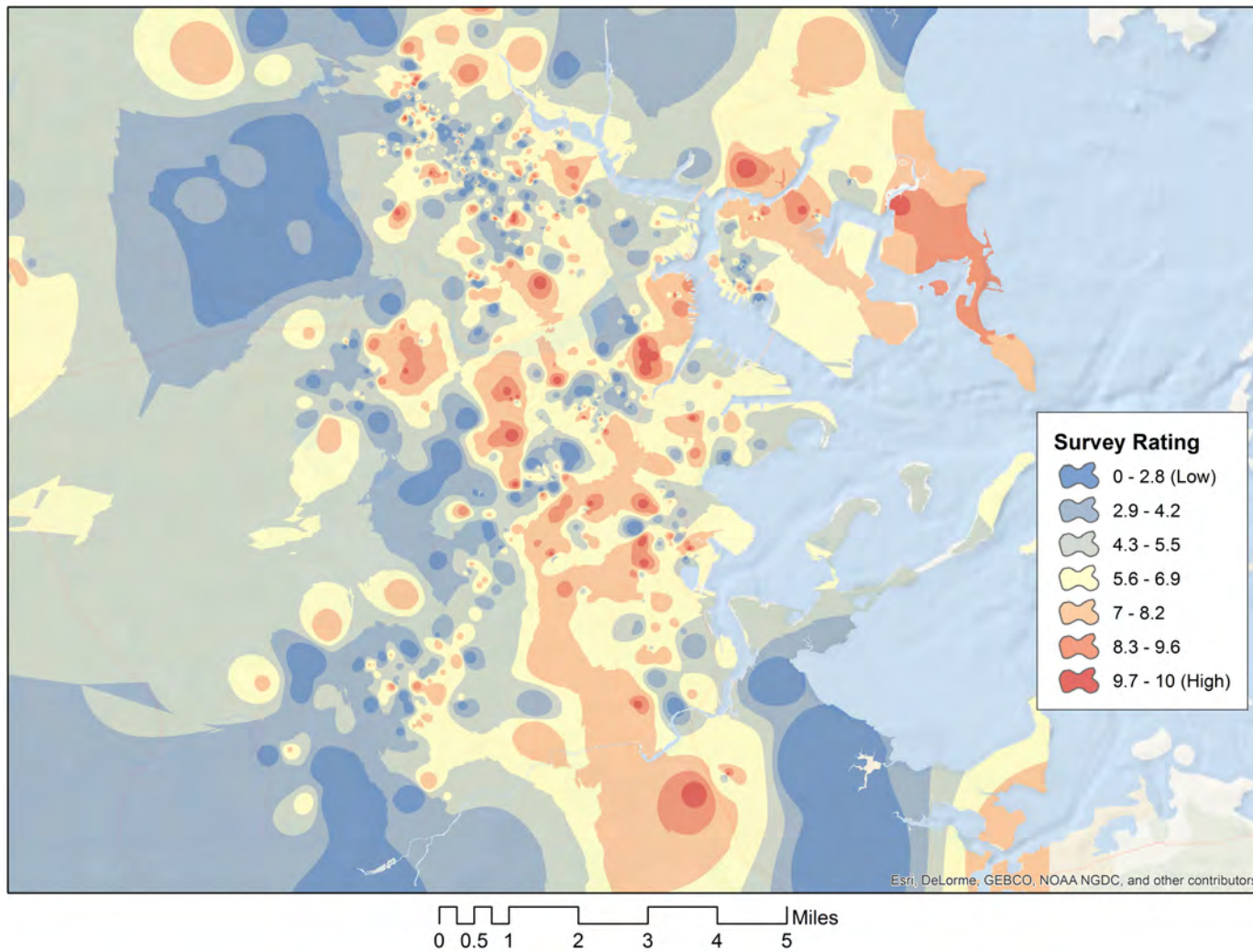


Figure 13: Neighborhood sound annoyance levels map.

Looking at the literature, however, it is relatively deep, albeit awash with operational, regulatory, and performance assumptions to constrain this problem. Across the board, there is consensus in literature that if deployed deliberately, small UAV-LMD services delivering small payloads over short distances could almost halve CO₂ emissions as compared to the same set of demand being served by a traditional ground-based diesel delivery vehicle (Goodchild and Toy, 2018). These results depend on a variety of assumptions – upstream energy generation fuel sources, warehouse networks design, or UAV battery technology improving in the coming years. Findings also suggest that as UAV size, distance, and payload weight increase, these savings do not scale linearly, but rather UAV emissions tend towards that of a typical diesel ground vehicle (Stolaroff, 2018).

Aside from CO₂ emissions, there exists a series of other sustainability concerns pertinent to the UAV-LMD discussion. A broader life-cycle analysis of the UAVs, infrastructure, components and equipment necessary is also vital to fairly assess UAV-LMD’s long-term sustainability feasibility (Figliozzi, 2017). A life-cycle analysis usually involves all the necessary steps to consume a product, the product being UAV-LMD for consumer packaged goods (CPGs), foods or other consumer goods, including raw material production, manufacturing, distribution (the UAV-LMD step that this report predominantly focuses on), disposal and auxiliary transportation requirements. A large part of the vehicle disposal carbon footprint is the degradation and disposal of the lithium-ion polymer battery. Because of their long charge times and general ease of exchange, some UAV-LMD operators may allo-

cate multiple battery packs per UAV platform. This enables higher utilization of the UAV asset that, over the course of the asset lifetime, is re-captured in saved CAPEX and extra labor costs in asset down times.

There is little to no regulatory pressure to minimize UAV-LMD emissions, however, minimizing 1) the CAPEX costs of UAVs or lithium-ion batteries that are no longer functional; and 2) electricity costs in charging depleted batteries; and 3) under-utilized labor costs when assets are grounded (for battery charging or otherwise), is fundamentally aligned minimizing life-cycle and routing emissions for UAV-LMD. In assessing what all of these sustainability implications mean for operational constraints, this report discerns the following incentives for UAV-LMD players designing their operations:

- to efficiently combine customers in single trips in a one-to-many versus a one-to-one delivery manner to avoid unnecessary line-haul energy consumption patterns, increased battery switching time delays and labor costs and battery degradation both from a cost and sustainability perspective;
- to find the trade-off between excessive payload weight with the associated non-linear increase in energy consumed and repeated flights;
- to fly at lower altitudes to minimize unnecessary energy consumed in vertical take-off and landing maneuvers; and
- minimize flight distances and fly point-to-point as much as possible adhering to strict no-fly zones.

Translating into Modeling Extensions



4 Translating into Modeling Extensions

This section summarizes this report, highlighting the specific exogenous societal and regulatory constraints that are likely to constrain future operations. This report aggregates each potential constraint mentioned in this report into specific operational constraint pathways that operators will likely need to adhere to or be aware of. These constraint pathways are: 1) altitude minimums and maximums; 2) MTOW constraints; 3) flight restrictions; and 4) maintenance and pre-flight checks.

Altitude minimums and maximums. All UAVs are to cruise in the 200-400 ft. altitude range and adhere to region-specific altitude minimum requirements. There may also exist urban structures that extend beyond the 200 ft. altitude minimum forcing UAVs to maintain a 200 ft. lateral and 50 ft. vertical clearance. Furthermore, due to the in-air separation constraints, depending on the UAV heading, it should adhere to the altitude stratification protocol depicted in Figure 14. Additionally, because of the environmental concerns and incentive to minimize energy consumption, UAVs would likely attempt to cruise at their lowest permissible cruise altitude given the aforementioned constraints. The UAV are likely to ascend to their minimum-permissible cruise altitude based on its flight trajectory and remain at that altitude for the flight duration instead of performing a staged ascent. See Figure 15 for a pictorial example of this logic.

MTOW constraints. The total UAV weight should not exceed 55 lbs. throughout the duration of its route. This constraint would extend beyond MTOW since UAVs can pick up customer demand, meaning in-flight operating weight can exceed MTOW unlike traditional commercial passenger aircraft.

Flight restrictions. UAVs would strictly adhere to FAA instituted no-fly zones at all times. The types of locations included in the flight zoning restrictions would vary based on the intensity of the local zoning restrictions. To minimize energy consumption, flight trajectories could be plotted around flight zoning restrictions leveraging a route planning algorithm such as the visibility graph algorithm. A quick side: A visibility graph is a computational geometry methodology often used in robot motion and trajectory planning given a confined feasible region of operation. Within this region, a set of start and end points exist as well as a set of obstacles that any agents cannot enter into. With this initial state, a visibility graph initializes nodes at each point in the region and at each corner of each obstacle. It then builds edges from every node to every other visible node, a visible node defined as a node that can be reached in a straight line from the start node without intersecting with any obstacle boundaries. Thus, when the visibility graph is queried to get the shortest path between two points, a shortest-path algorithm, such as the popular A*-Algorithm, is employed whilst only traversing existing edges.

Maintenance and pre-flight checks. All UAVs would likely need to adhere to a maintenance and pre-flight check schedule in line with the expected industry standards as defined with industry partners.

The magnitude of the associated time delays varies would be governed by drafted regulation and/or self-imposed safety protocols and expectations.

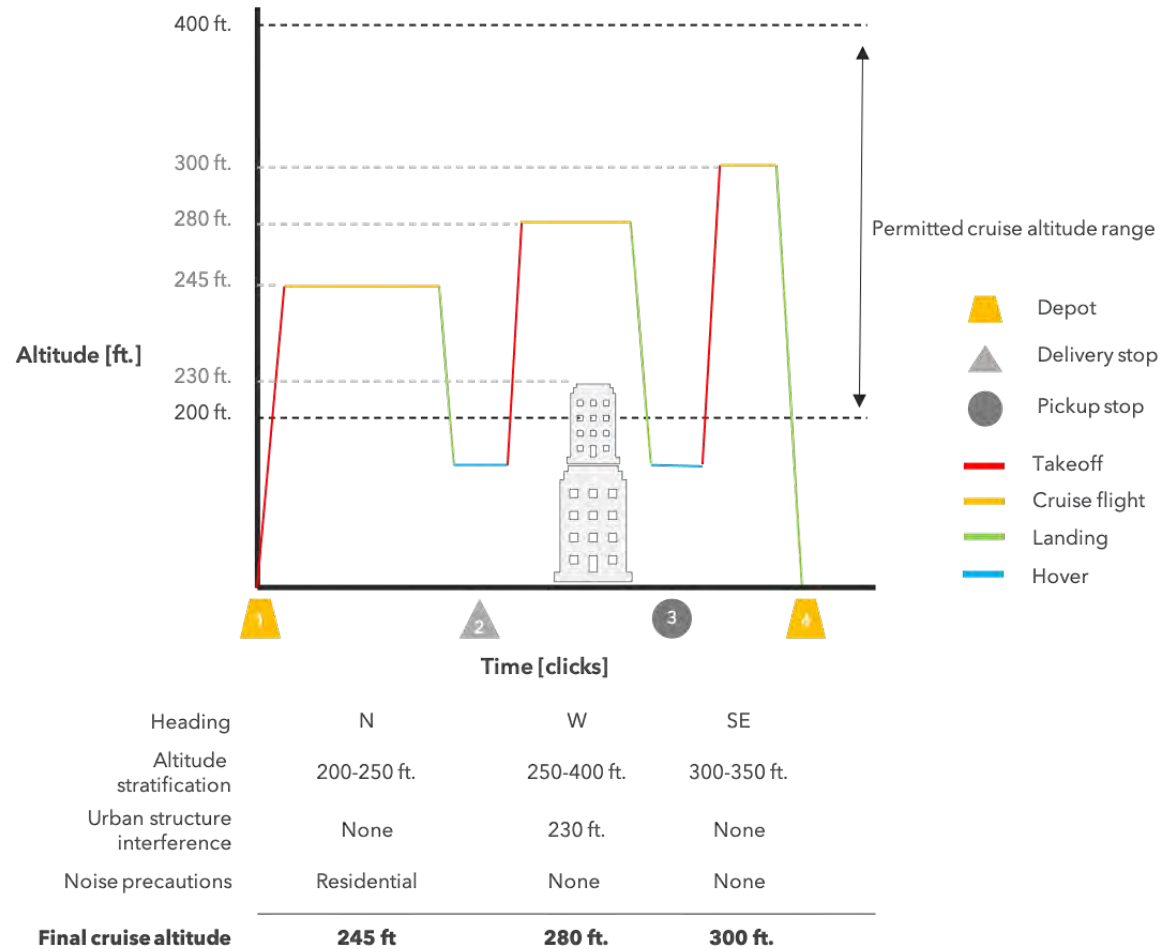


Figure 14: Cruise altitude determination logic aggregating exogenous constraints.

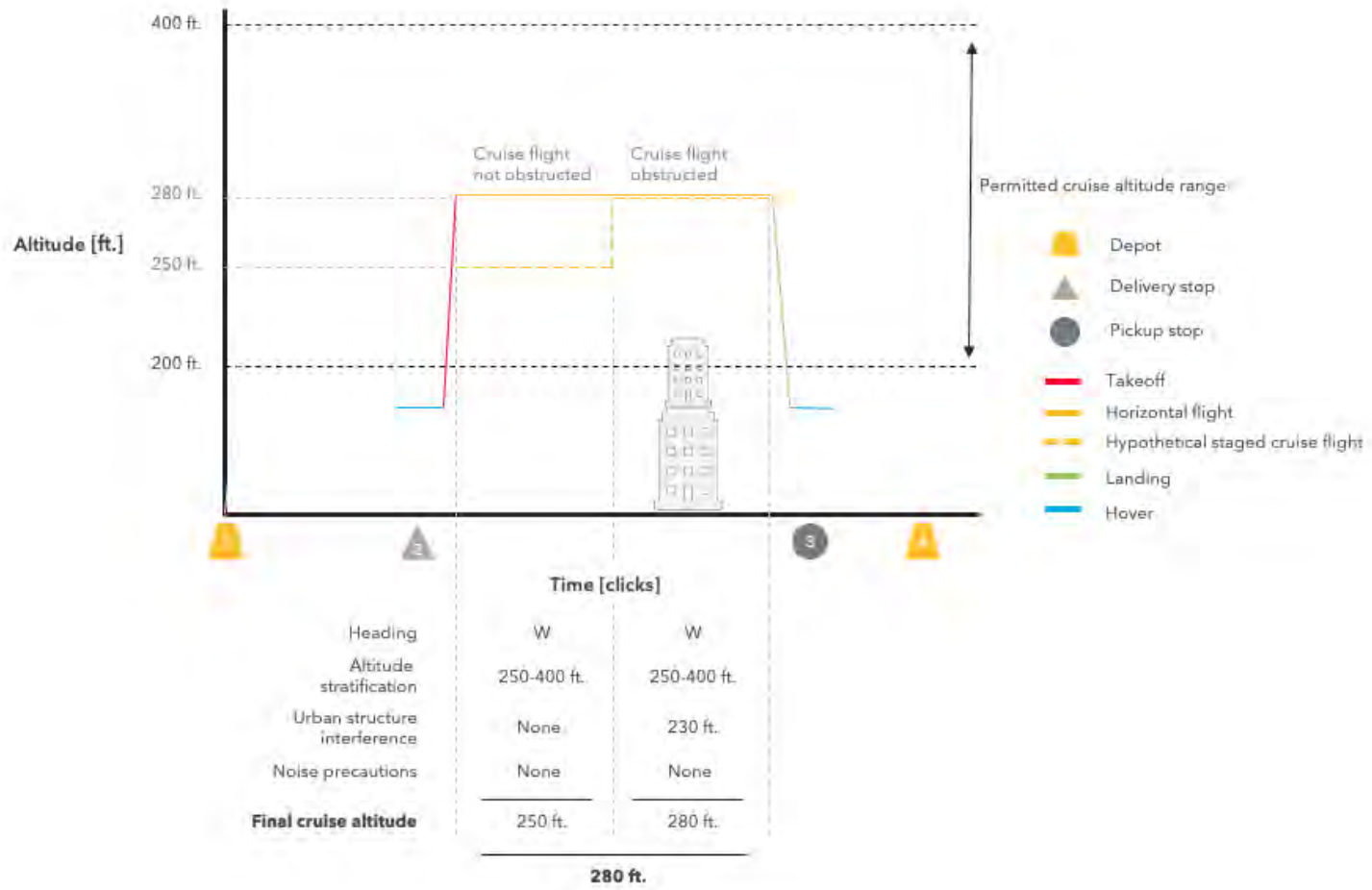


Figure 15: Pictorial illustration of non-staged cruise altitude determination logic, expanded illustrative example for UAV traversing arc between nodes.

Conclusion



5 Conclusion

This report offers insight into the various societal and regulatory factors that will likely shape UAV-LMD operations in the immediate and near future. It does so by introducing the motivations and promise behind UAV-LMD, surveying the status quo and potential future trajectory of pertinent regulation, and exploring the potential negative externalities UAV-LMD might impart on society that could be, themselves, translated into self-constraining or regulated operational constraints.

The key societal and regulatory constraints that are likely to translate into UAV-LMD operations are identified via seven key operational modeling restrictions in the near- to medium-term. These constraints are identified based on the survey of regulatory material as well as academic and industry literature. This report notes that there are many pathways for regulators, both local and federal, to enact policies in the aim to counteract any specific externality of UAV-LMD. Unless penned into law or proposed in currently deliberated bills in the U.S. Congress, there is little to no historical evidence as to which avenue will likely be adopted to protect against a particular externality. In this way, this report highlights the immense levels of regulatory uncertainty surrounding UAV-LMD. One potential source of regulatory inspiration this report identifies lies in the ways in which commercial passenger airlines are currently regulated and operationally constrained today. In this process, this report uncovers that many of the regulatory frameworks that exist in the commercial airline domain are not wholly reflected in apposite UAV-

LMD regulation today. Thus, there remains room for regulators to leverage existing commercial aviation regulation and draft similarly constraining policies for UAV-LMD in the coming years.

Of these societal and regulatory constraints discussed in Sections 2 and 3, the most well delineated and patent constraints today are the altitude minimums and maximums, operating weight constraints, and flight zoning restrictions which all exist in statute. The remaining constraints are amalgamations of tangentially apposite regulation or historical case law. The societal barriers to UAV-LMD have not been clearly represented in drafted regulation but only via proposed regulation such as the “Drone Integration and Zoning Act of 2019”, and manifest in operational constraints as altitude minimums and maximums and flight zoning restrictions.

It is worth noting, however, that UAV-LMD as a business model, and area of operations and policy research is still in its infancy. As a result, there remain many domains of significant uncertainty surrounding various dimensions of UAV-LMD: UAV technology and technological progression, markets and a definitive use-case, infrastructure requirements and its impact on operations, regulation or societal acceptance to name but a few potentially derailing factors. In this light, whilst the approach this report adopts, by and large, avoids areas that require significant assumptions to be made, simplifying assumptions are likely necessary in any holistic systems-level analysis of a budding industry and technology.

One key limitation is that the broader societal and regulatory con-

straint analysis this report undertakes is a snapshot of the current UAV-LMD landscape and does not take into account any public or regulatory evolution in any of the specific issues raised. The analysis did attempt to project each specific issue into the future but limited this effort because of a dearth of literature or historical grounds to form such opinions. This report opts for a more measured approach to evaluating the potential societal and regulatory considerations because, in many ways, the motivation of this report is to uncover the value of a holistic, society-centric approach to UAV-LMD operations to offer avenues for future research.

UAVs deployed to fulfill last-mile delivery demand stand to disrupt the status quo for how societies transfer goods across geographic landscapes and mega-cities. They have the potential to help make cities more environmentally sustainable, equitable and economically productive, unlocking what some term the sharing economy. Individuals across social classes and geographies could have greater access to a

breadth of goods and services unlike ever before in the history of our societies. This has implications for urban planners as it recasts the notion of cities, suburbs and commuting arteries. They are on the cusp of disrupting the last-mile industry and offer service levels at costs that have historically been unreachable.

Faced with these untold opportunities but set of challenges, the last-mile industry and its various stakeholders have an opportunity to define a future for UAV-LMD and its stakeholders. A more likely postulation is that the “last-mile” delivery problem is unabating and will continue to pressure key industry players to innovate with new technologies, operational models or business models. The technology policy question will remain central to UAV-LMD in the coming years. But where there are problems, there are opportunities. Undoubtedly, societies, cities, regulators, and logistics players with a stake in solving the “last-mile” problem are in strong position to capitalize on its opportunities.

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List of Acronyms

AGL above ground level

AR augmented reality

ATC air traffic control

BVLOS beyond visual line of sight

CAAC Civil Aviation Administration of China

CAGR compound annual growth rate

CAPEX capital expenditures

ConOps concept of operations

CPG consumer packaged good

CS control station

DC distribution center

DDP drone delivery problem

DEP distributed electric propulsion

DOT Department of Transportation

EA Exact Approach

ECDF empirical cumulative distribution function

EPA Environmental Protection Agency

ETSA Exact Two-Staged Approach

ETSA-2 Exact Two-Staged Approach Stage-2

ETSA-1 Exact Two-Staged Approach Stage-1

EU European Union

EVLOS extended visual line of sight

FAA Federal Aviation Administration

FAR Federal Aviation Regulations

FCC Federal Communications Commission

FMCSA Federal Motor Carrier Safety Administration

FRA FAA Reauthorization Act

GDPR General Data Protection Regulation

GPS Global Positioning System

GURP generalized unmanned aerial vehicle routing problem

HA Heuristic Approach

IFR Instrument Flight Rules

IMSAFE illness, medication, stress, alcohol, fatigue, emotion

KPI key performance indicator

LAANC Low Altitude Authorization and Notification Capability

MILP mixed-integer linear program

MSL mean sea level

MTOW max take-off weight

NAS The National Airspace System

NASA The National Aeronautics and Space Administration

NHTSA The National Highway Traffic Safety Administration

NTIA National Telecommunications and Information Administration

OEM original equipment manufacturer

OR operations research

PAR planned adaptive regulation

PAVE personal/pilot, aircraft, environment, and external pressures

R&D research & development

SMS short message service

STEM science, technology, engineering, and mathematics

TFR Temporary Flight Restriction

TW time window

U.S. United States

UAE United Arab Emirates

UAS unmanned aerial system

UAV unmanned aerial vehicle

UAV-LMD unmanned aerial vehicles for last-mile delivery

UK United Kingdom

UPS United Parcel Service

URP unmanned aerial vehicle routing problem

USPS United States Postal Service

UTM unmanned aircraft system traffic management

VC venture capital

VFR Visual Flight Rules

VLOS visual line of sight

VRP vehicle routing problem

VRPD vehicle routing problem with drones

VTOL vertical take-off and landing

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