Measuring the Effects of Drone Delivery in the United States

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Report prepared by the Virginia Tech Office of Economic Development and the Grado Department of Industrial & Systems Engineering

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Executive summary

The growth of e-commerce is driving increased demand for fast, reliable and affordable delivery across the "last mile." Industry is developing new ways to respond to this demand. One example is delivery by drone. In 2019, the Federal Aviation Administration (FAA) certified the first commercial drone delivery services in the United States. Since this research began, social distancing guidelines have been imposed for COVID-19, substantially increasing the demand for cost-effective and contactless delivery.

This report measures the potential impact of drone delivery for consumers, local businesses and communities across the U.S. It examines three representative metropolitan areas to illustrate the benefits of drone delivery as well as the demographic, geographic, technical and policy conditions necessary to realize those benefits. Existing research explores the long-term impact of drone delivery. Uniquely, this study quantifies the short-term benefits within one to five years of introduction, taking a mixed-methods approach that combines qualitative interviews and surveys, traditional consumer surplus modeling and simulation modeling to develop a robust set of findings.

The Virginia Tech team selected three metropolitan areas—Christiansburg, Virginia; Austin, Texas; and Columbus, Ohio—that represent cities with varying population densities and transportation challenges. Based on existing drone capabilities, we examined drones that carry five pounds or less, travel at high speeds of up to 80 miles per hour, have a five-mile operating range, and can match or exceed existing delivery services for cost and convenience. We then explored three types of potential beneficiaries of drone delivery: consumers, local businesses and the broader community, including the environment.

Our findings suggest that drone delivery can improve the lives of **consumers** by expanding access to services, reducing unnecessary travel and saving time. The benefits are pronounced for those who face mobility challenges or live in areas underserved by other transportation options. Drone delivery benefits **local businesses** by increasing their customer reach, improving their response times and increasing their sales, potentially at a lower cost than alternative delivery models. Finally, drone delivery benefits **communities** by reducing vehicle traffic, CO_2 emissions and road accidents, as well as improving access to healthy foods, medicine, and other essential supplies that support long-term health outcomes.

By Year Five, in a single U.S. metropolitan area, drone delivery could:

- Serve up to **53.9%** of the population;
- Recover up to **$582.5 million per year** in total time savings for consumers;
- Support the **3.6-6.6%** of metropolitan residents who lack access to a vehicle (as many as **66,000 people** in a single metropolitan area);
- Help **22,000 people** with mobility challenges to obtain their prescription medication;
- Generate up to **$284,000 per year** in new annual sales for a participating local business (up to **250%** additional sales compared to a scenario without drones);
- Avoid up to **294 million miles per year** in road use and up to **580 car crashes per year**;
- Reduce up to **113,900 tons per year** of CO_2 emissions, equivalent to **46,000 acres per year** of new forest.

Variations exist between cities based on a range of variables including size of the existing market, demographics, population density and urban environment. For example, in communities with greater distances between commercial centers and residences, consumers may benefit more from drone delivery through time saved – as much as **31-56 hours of time saved per person per year**, averaged across all residents. In denser communities with high costs of living, consumers may benefit more from the *value* of time saved – as much as **$323.5-582.5 million per year in total time savings**.

The following table summarizes the potential benefits of drone delivery by Year Five of adoption for each of the three metropolitan areas. The benefits vary based on adoption rate, demographics, population density and urban environment. Policy implications of this research include the importance of responsible operations for social acceptance and ongoing collaboration between industry and local communities.

Table 1: Benefits to consumers, businesses and the community by Year Five

	Lower density (Christiansburg, Virginia)	Medium density (Austin, Texas)	Higher density (Columbus, Ohio)
Consumers	Serve **92,200 people** in the service area, **50.7%** of the total metropolitan population (across 2 commercial centers) Recover **$23.0-45.9 million** in time savings for consumers using drones	Serve **1,077,800 people** in the service area, **53.9%** of the total metropolitan population (across 7 commercial centers) Recover **$323.6-582.5 million** in time savings for consumers using drones	Serve **1,000,300 people** in the service area, **49.4%** of the total metropolitan population (across 7 commercial centers) Recover **$219.8-403.8 million** in time savings for consumers using drones

	Lower density (Christiansburg, Virginia)	Medium density (Austin, Texas)	Higher density (Columbus, Ohio)
Consumers	Support **3,380 people** in the service area who lack access to a vehicle Help **1,340 people** with mobility challenges to obtain their prescription medication, with up to **$1.3-59.3 million** in annual healthcare benefits	Support **39,000 people** in the service areas who lack access to a vehicle Help **20,000 people** with mobility challenges to obtain their prescription medication, with up to **$18.7-872 million** in annual healthcare benefits	Support **66,000 people** in the service area who lack access to a vehicle Help **22,000 people** with mobility challenges to obtain their prescription medication, with up to **$20.6-959 million** in annual healthcare benefits
Businesses	Generate **$25-73,000 per year** in additional sales for participating retail businesses Generate **$38-71,000 per year** in additional sales for participating full-service restaurants Generate **$94-174,000 per year** in additional sales for participating limited-service restaurants	Generate **$72-208,000 per year** in additional sales for participating retail businesses Generate **$79-145,000 per year** in additional sales for participating full-service restaurants Generate **$154-284,000 per year** in additional sales for participating limited-service restaurants	Generate **$34-97,000 per year** in additional sales for participating retail businesses Generate **$54-99,000 per year** in additional sales for participating full-service restaurants Generate **$95-176,000 per year** in additional sales for participating limited-service restaurants
	Generate **50-165%** sales growth for participating retail stores and **121-250%** sales growth for participating restaurants compared to no drone delivery over the five-year period.		
Communities	Reduce vehicle travel by **18.7-30.5 million miles per year** in the service area**,** equivalent to **13.5-14.5%** of all delivery and pickup cars Save **7.2-11.7 thousand tons of CO_2 per year** in the service area, equivalent to **2.9 -4.7 thousand acres** of new forest Prevent as many as **28-46 car crashes per year** by reducing road travel	Reduce vehicle travel by **145.2-294.0 million miles per year** in the service area, equivalent to **11.1-13.6%** of all delivery and pickup cars Save **56.1-113.9 thousand tons of CO_2 per year** in the service area, equivalent to **22.7- 46.0 thousand acres** of new forest Prevent as many as **287-580 car crashes per year** by reducing road travel	Reduce vehicle travel by **95.8-183.2 million miles per year** in the service area, equivalent to **9.4-10.7%** of all delivery and pickup cars Save **36.5-69.9 thousand tons of CO_2 per year** in the service area, equivalent to **14.6-27.9 thousand acres** of new forest Prevent as many as **244-466 car crashes per year** by reducing road travel

Introduction

The transportation of goods is evolving rapidly in response to changing customer expectations, the growth of e-commerce, and the emergence of new technologies. Industries are developing new ways to respond to this increased demand for faster, more reliable, and cost-effective delivery services. For example, automated technology, such as unmanned aerial systems ("drones") could enable rapid, efficient and low-cost delivery of small goods in cities across the "last mile." A 2018 survey of 1,100 manufacturing and supply chain leaders showed that 53% of respondents believed that driverless vehicles and drones have the potential to create competitive advantages and disrupt the industry, compared to just 30% in 2015.[1] The potential effects of drone delivery for consumers, businesses and the broader community are emerging areas of research.

In this study, a team of researchers at Virginia Tech investigated how drone technology might benefit last mile delivery in different U.S. metropolitan areas. The drone industry is diverse, with a wide range of drone types and operations. Based on existing commercial delivery services, we limit the analysis to drones that carry five pounds or less and travel at high speeds of up to 80 miles per hour over short distances of up to five miles. Specifically, we examined the potential benefits of drone delivery for restaurants, pharmacies, retail businesses that use traditional parcel delivery, and retailers of smaller items who currently do not offer delivery. The following questions served as a framework for our research:

- How can drones be used to meet increased demand for timely last mile delivery, complementing existing delivery technologies?
- How are consumers, businesses, cities and the environment affected by the integration of drones into these industries?
- What are the policy implications of this technology?

Understanding drone delivery becomes even more pressing in light of developments such as the COVID-19 pandemic that have caused consumers to modify everyday habits. Today, social distancing has become a way of life for many cities and states. As of April 2020, consumer visits to restaurants, shopping centers, and other recreational stores is down as much as 35-40% in states such as Ohio, Texas and Virginia.[2] Although social distancing and stay at home orders may not continue for long at this scale, it could permanently change consumer behavior, and reinforce existing trends towards e-commerce and on-demand delivery. Drone delivery promises less contact with other individuals while meeting consumer demands for timely and cost-effective delivery. This type of delivery could support changing consumer behaviors over the long term.

The following report provides a brief review of current drone delivery research and then analyzes three growing U.S. metropolitan areas that represent a range of different U.S. regions:

Christiansburg, Virginia; Austin, Texas; and Columbus, Ohio. The report examines each of these metro areas individually to determine how drone delivery might operate and quantify potential benefits. Finally, the report identifies key customer demographics and business types that may benefit from drone delivery; applications for drone delivery that may have wider social benefits; and the policy implications of drone delivery.

Growing demand for e-commerce provides an opportunity for drone delivery

U.S. e-commerce is growing rapidly at a rate of 10.5% annually between 2014 and 2019. In retail, e-commerce sales for the second quarter of 2019 (which excludes restaurant purchases) totaled an estimated $146.2 billion, accounting for 10.7% of total U.S. retail sales. The growth of retail e-commerce exceeded the growth of retail generally. By comparison, total retail sales only increased by 3.3% annually during the same period.[3] E-commerce is projected to continue as a key external driver of retail sector growth. Major e-commerce growth will likely occur in groceries, major appliances, and clothing, all of which are traditionally dominated by brick-and-mortar shopping.[4]

Restaurant delivery services are another area likely to experience major e-commerce growth. A 2016 survey conducted by the National Restaurant Association found that 37% of restaurants offer online ordering and 32% accept mobile payments.[5] Due to the COVID-19 pandemic and stay in place orders in most states, the current number of restaurants offering online ordering is likely much higher now. Food delivery sales through online sites and mobile apps may grow as much as 22.3% annually by 2024.[6] The explosion of food delivery apps and third-party delivery options is one driver of this growth.

Considering these trends, the total number of industry participants in e-commerce may grow as much as 11.6% annually over the next five years to 2024.[4] Rising competition is pressuring e-commerce businesses to offer better services, lower pricing, and faster shipping than their competitors. Fast and free shipping has been the top online shopping motivator for consumers since 2013, particularly for consumers under the age of 25.[7]

Delivery has become more important as customer expectations of online shopping are shaped by the emergence of two-day, one-day, and same-day shipping, driven largely by the delivery policies of major e-commerce marketplaces such as Amazon. For example, approximately 15% of customers reported they bought a product on Amazon that is more expensive than other online retail sites due to the attractiveness of two-day delivery.[8]

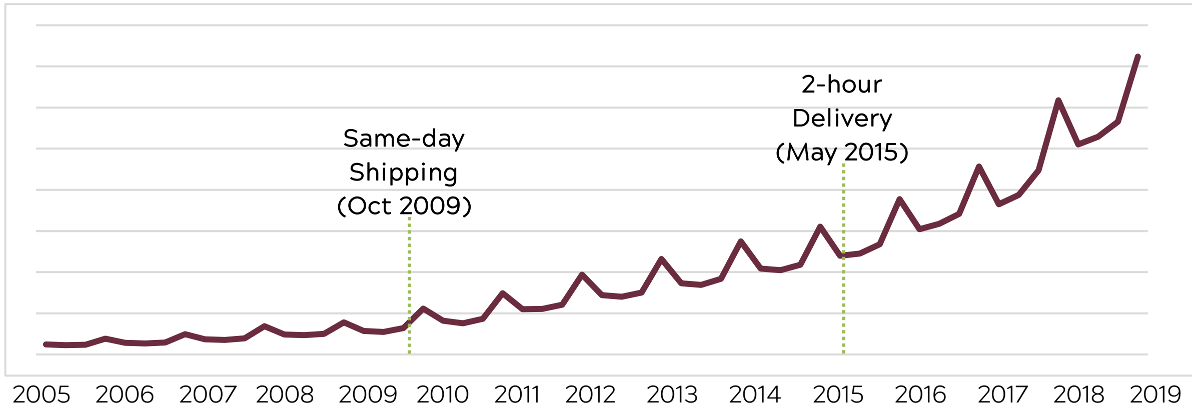

Figure 1: Acceleration of Amazon's growth after implementing same day and two-hour delivery options

The introduction of same-day shipping in 2009 and two-hour delivery in 2015 accelerated growth in Amazon's total revenue (Figure 1).[9] After each of these shipping changes, sales grew 27.4% annually on average in years two and three. Growth continued, but slowed to 12.4% annually on average, in years four and five. These growth rates can be visualized as an S-curve (see Figure 2 in the 'Methodology' section). The immediate market reaction shows that faster delivery attracts more customers, boosts sales, and improves satisfaction among customers. Even so, only 15% of customers report that online retailers always offer shipping options that fulfill their high-speed delivery needs.[7]

Methods

Achieving the benefits of drone delivery depends on the adoption of drones as a delivery method. Widespread adoption is determined by a number of factors, including service coverage, reliability and cost. In particular, businesses and consumers will use the technology if the drone delivery industry:

- Demonstrates that drones can be safely integrated into complex airspace and populated environments;
- Demonstrates that drones can be responsibly integrated into communities; and
- Achieves a level of efficiency and automation to make operations scalable and cost effective for businesses and consumers.

This study focuses on drone delivery for retail goods (including groceries) and restaurant orders that weigh five pounds or less. Five pounds approximates the maximum payload existing small delivery drones can carry. The drones were modeled to have up to a five-mile operating range at speeds of up to 80 miles per hour. Road-based delivery options are often limited by the availability of vehicles and drivers, speed, and the price of delivery. Ideally, drone delivery will match or exceed existing delivery modes for availability, speed, and price to drive adoption.

Understanding the adoption rate

Many disruptive technologies follow an adoption pattern, where consumers start slowly, then accelerate, before stabilizing, essentially following an S-curve. Similarly, in this research, we assume the adoption of drone delivery by consumers starts slowly (Year One), and speeds up (Year Three) before stabilizing (Year Five). To account for variations in the potential consumer adoption rate, we constructed three scenarios for drone adoption, as illustrated by technology adoption S-curves (Figure 2). The three different S-curves in Figure 2 represent potential adoption scenarios based on observed trends from existing delivery models:

- **Scenario 1 (e-commerce growth only):** Drone delivery helps adopting businesses to keep up with growing U.S. demand for e-commerce, which represents about 10% growth in sales each year. In this scenario, businesses use drones for delivery, but drones do not motivate consumers to make more purchases from participating businesses.
- **Scenario 2 (moderate drone boost):** Drones are used by businesses. Improved delivery service motivates consumers to buy more goods from participating businesses. Businesses that use drones increase their sales by 13.7% per year in Year Three and 6.2% per year in Year Five.

- **Scenario 3 (high drone boost):** Drones are used by businesses and play a substantial role in motivating consumers to buy more goods from participating businesses. Businesses that use drone delivery increase their sales by 27.4% per year in Year Three and 12.4% per year in Year Five. We base these growth rates on observed sales trends of existing delivery services (see e-commerce section above).

Note that the rate of adoption stabilizes over time. Therefore, additional sales *year-on-year* are greater in Year Three than Year Five, although *total* additional sales are greatest by Year Five.

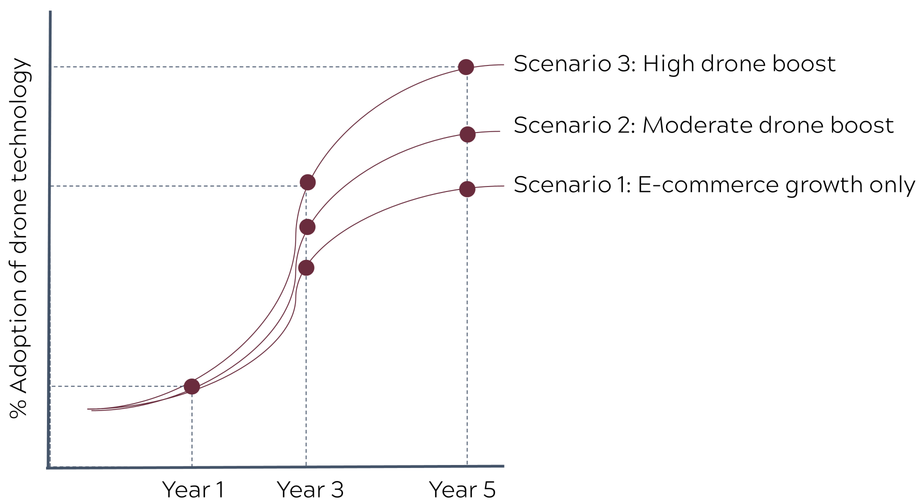

Figure 2. Adoption scenario s-curves

Selecting cities for data collection

We applied these scenarios to businesses in three metropolitan statistical areas (MSAs) of different population densities and demographic characteristics: Blacksburg-Christiansburg-Radford, Virginia; Austin, Texas; and Columbus, Ohio. To select these cities, we started by identifying metropolitan areas that might be well suited for drone delivery, including those with:

- Lower population density (i.e. highly distributed layout): indicates geographic spread, which may suggest transportation and logistics challenges. While many of the larger MSAs are over 1,000 people per square mile, we chose metropolitan areas with fewer than 600 people per square mile, with density varying between 170 and 510 people per square mile;
- Recent population growth: indicates a growing market, which may place greater strain on existing infrastructure;
- High percent of detached housing: indicates that the property may have yards or other spaces accessible for drone delivery; all three metropolitan areas had about 60% detached/single-family housing.

Using these variables, we narrowed down to 12 metropolitan areas, and examined the distribution of commercial centers, demographics and traffic congestion challenges that drones could alleviate. We invited six communities to participate in the study, and three responded with interest: Blacksburg-Christiansburg-Radford, Virginia MSA (lower density MSA); Austin, Texas MSA (medium density MSA); and Columbus, Ohio MSA (higher density MSA). The Blacksburg-Christiansburg-Radford MSA is referred to as Christiansburg, Virginia in this report because the town serves as the county seat. Table 2 summarizes the demographic characteristics of these three metro areas.

Table 2. Demographic characteristics of the three metropolitan areas[10]

Metro area	Population change (2014-2017)	Total population (2017)	Population density (per square mile)	Percent of population ages 18-54	Median household income (2017 inflation adjusted dollars)	Percent of occupied single-family housing units (with yards)
Blacksburg-Christiansburg-Radford, VA	0.2%	181,863	170	57.2%	$50,409	62%
Austin, TX	9.0%	2,000,590	474	55.7%	$69,717	61%
Columbus, OH	3.9%	2,023,695	510	51.8%	$60,170	64%

Determining the number of participating businesses

From interviews with retail and restaurant establishments in these three metropolitan areas, the team determined that approximately 55% of deliveries and pick-up orders for each business are less than five pounds. Thus, for all years, the model converts no more than 55% of business deliveries and pick-up orders into drone deliveries.

While consumer adoption follows the S-curve scenarios illustrated in Figure 2, each scenario also involves increased business participation over time. Thus, we hold business participation across the three scenarios (i.e. e-commerce growth only, moderate drone boost, and high drone boost) constant while increasing the number of participating businesses from Year One through Year Five. Table 3 on the next page illustrates the number of businesses adopting and the number of participating commercial centers in each metropolitan area by year. We define a commercial center as a particularly dense cluster of commercial businesses. To standardize across localities, we drew five-mile radiuses and borders around these clusters to represent each "commercial center". These centers not only have an assortment of retail and restaurant businesses, but also single-family household residencies. Initially, Christiansburg has one modeled commercial center. Austin and Columbus each have two modeled commercial centers.

In Year One, five businesses within a commercial center are assumed to adopt drone delivery. A portion of their current delivery sales are converted to drone delivery. By Year Three, 15-25% of businesses that currently use in-house or third-party delivery also use drones in each modeled commercial center. By Year Five, approximately 75% of businesses that currently use in-house or third-party delivery also use drones in each modeled commercial center.

Finally, we assume that additional commercial centers are added in Year Five to meet increased demand for drone delivery services and to support approximately 50% of the metropolitan population. In addition to the modeled commercial centers, there is one more commercial center using drones in the Blacksburg-Christiansburg-Radford MSA (now servicing 51% of the MSA population), five more commercial centers in the Austin MSA (now servicing 54% of the MSA population), and five more commercial centers in the Columbus MSA (now servicing 49% of the MSA population).

For the five additional commercial centers in Austin and Columbus, we extrapolated data from the original modeled commercial centers. To extrapolate, we identified commercial centers with similar physical characteristics and business types to the centers modeled and then scaled the modeled findings to the size (number of businesses) of each additional commercial center.

Table 3: Approximate number of businesses and commercial centers modeled each year

	Number / % of businesses participating in drone delivery in each commercial center	Number of commercial centers with data collection and modeling	Number of additional commercial centers with extrapolated data
Year One	5 businesses	1 in Christiansburg, VA 2 in Austin, TX and 2 in Columbus, OH	-
Year Three	15-25%	1 in Christiansburg, VA 2 in Austin, TX and 2 in Columbus, OH	-
Year Five	75%	2 in Christiansburg, VA 2 in Austin, TX and 2 in Columbus, OH	5 in Austin, TX and 5 in Columbus, OH

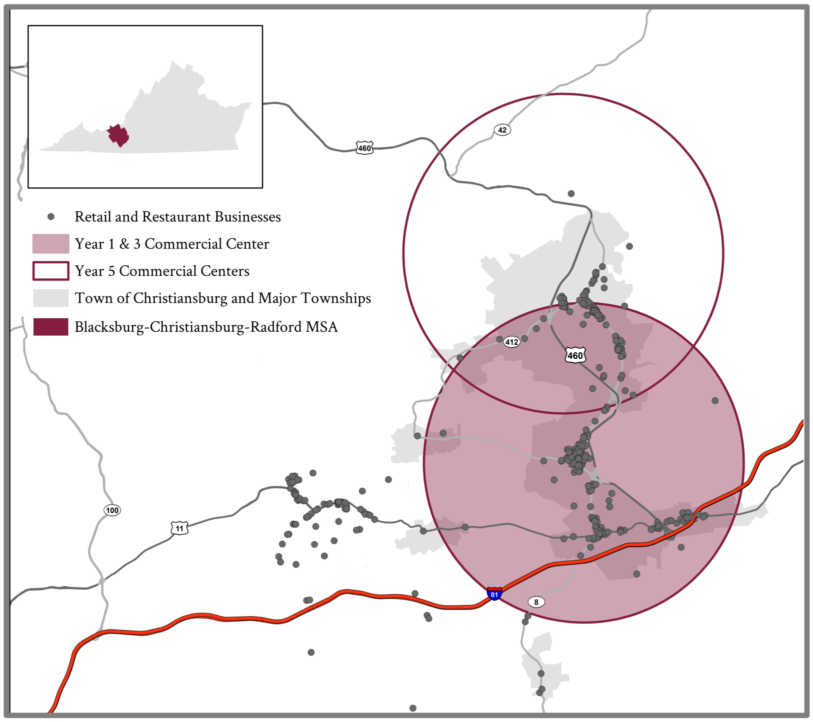

Figure 3: Simulation model for Christiansburg, VA

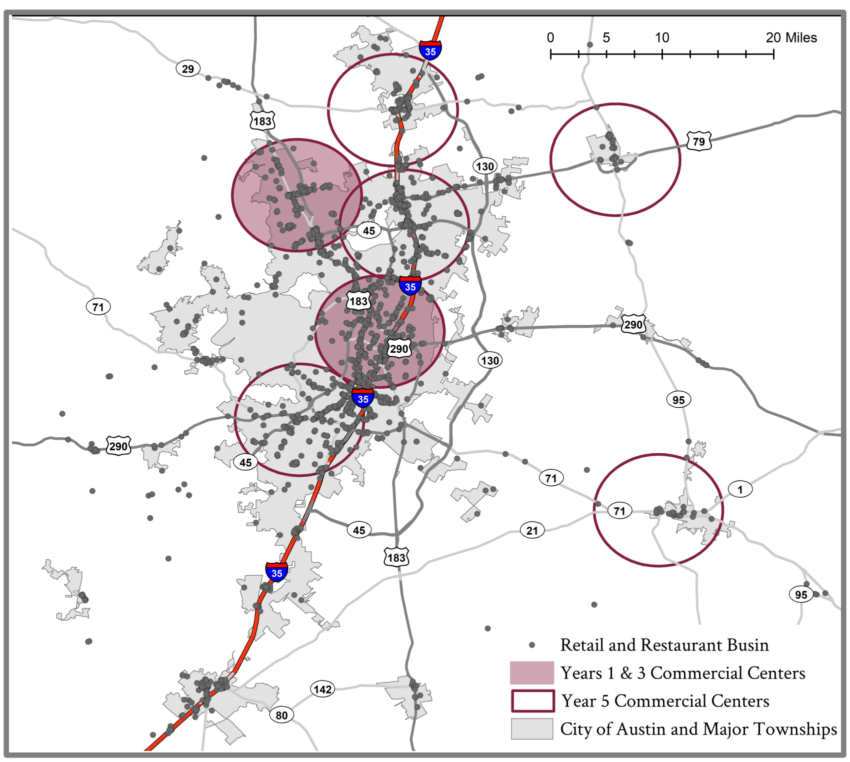

Figure 4: Simulation model for Austin, TX

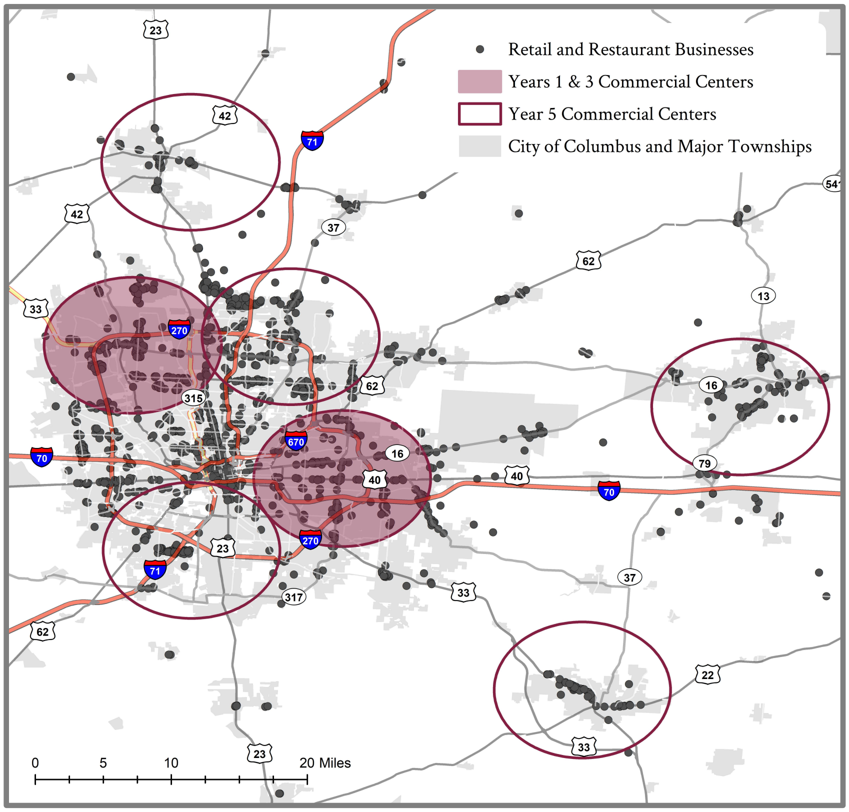

Figure 5: Simulation model for Columbus, OH

Modeling the benefits

To model and project the benefits of drone delivery, the research team relied on primary and secondary data, and both qualitative and quantitative data. We created a database for the modeled commercial centers in each metropolitan area to capture data for individual stores that could deliver products via drone. We gathered secondary data from different online data sources including the proprietary economic software EMSI Developer, Google, delivery apps, and store websites. Data included average time spent in store, delivery and pickup options, and the cost of delivery to consumers for each business.

To supplement this data, the research team visited these commercial centers and conducted 15-20 in-person business interviews (over 65 in total) to gather data on the number of orders per day, the average percentage of sales that are delivery and pickup, average time taken to prepare delivery and pickup orders, key products for drone delivery, and the average percentage of products weighing less than five pounds. We also asked about a store's willingness to deliver via drone, their experience with third party delivery services and any concerns they may have with drone delivery. Finally, we interviewed government officials in each locality. This included economic developers, chamber of commerce directors, transportation planners, and local elected officials.

Accounting for the three different scenarios and business participation growth in three different metropolitan areas, the research team modeled the impacts on consumers, businesses and communities.

Methodology for assessing benefits to consumers

Increasing customer demand for faster delivery challenges retailers, particularly smaller and individual businesses, to meet delivery standards shaped by large companies, such as Amazon and Walmart. This challenge offers a potential opportunity for drone delivery services as local businesses are likely to seek faster and more efficient delivery providers.

The immediacy of drone delivery can be highly competitive compared to other third-party delivery methods. For instance, Wing is a drone delivery service currently operating in Christiansburg, Virginia in the U.S., Canberra and Brisbane metropolitan areas in Australia, and Helsinki in Finland. Wing provides delivery services that average under ten minutes from order to delivery. The time reduction between dispatch and delivery can significantly improve convenience for customers.

To assess these benefits to consumers, we constructed a simple consumer surplus model, based on anticipated demand for drone delivery over a five-year period. Taking each scenario into account, we translated the total number of orders delivered via drone to the time saved by customers not having to drive to pick up their order. We then multiplied the average per-minute wage in the metropolitan area by the amount of time a consumer saves when she uses drone delivery instead of driving to pick up the order.

Additionally, we calculated the average time savings for different types of consumers to illustrate how different individuals may benefit. The four types of consumers are summarized in Figure 6 on the next page. The impacts for each consumer type appear in the results for each metropolitan area.

Chris: A single working professional. Chris is tech savvy, has limited free time, has a car, and adopts drones early. Because of the time savings, novelty and convenience, Chris uses drone delivery four times per week.

Taylor: A parent of two young children. Taylor is tech savvy, and has limited free time between working and childcare. For Taylor, drone delivery saves time and offers the ability to obtain household essentials without having to pack the kids in the car. Taylor uses drone delivery twice per week.

Darcy: A college student with high tech savvy and limited free time, although Darcy's schedule is flexible. Because of the novelty, time savings and convenience of not driving, Darcy uses drone delivery once per week.

Ari: An elderly person living in a local nursing home. Ari doesn't have a car. Drone delivery can help Ari to access food and household essentials that Ari otherwise might not be able to obtain. Drone delivery also helps Ari to adhere to their prescription medication. Ari uses drone delivery twice per month.

Figure 6: Four customer types

Methodology for assessing benefits to businesses

Drone delivery can also reduce costs to businesses and improve the efficiency of deliveries that are urgent or on-demand. Businesses that choose to adopt drones may experience an increase in sales due to both existing growth trends in e-commerce, and induced demand from improve delivery service (the "drone boost"). Drawing from proprietary data, we analyzed current sales of individual stores within each commercial center and projected how sales revenue would change in each of the three adoption scenarios. We examined impacts on retail stores (including grocery stories and pharmacies), full-service restaurants (sit-down restaurants), and limited-service restaurants (fast food and other restaurants that order at the register and do not have table service). Through interviews and surveys with businesses, we also developed preliminary assessments of how different business types might adopt and benefit from drone delivery (see the 'Results' section).

Methodology for assessing community and environment benefits

Drone delivery can reduce road use (i.e. fewer car miles and fewer cars), which generates additional benefits such as reduced CO_2 emissions and fewer car crashes. The Virginia Tech team developed a discrete event simulation model using Simio software to estimate these benefits. The model assumes that customers obtain their orders from businesses in two ways, either by pickups or deliveries.

Pickups involve the customer driving to a business, picking up their order, and then driving back to their neighborhood. Deliveries entail either a car or drone making the delivery to the customer. We assume a sufficient number of drones and cars are available to transport orders in the simulation. We also assume that dispatch technology is in place to coordinate the drone trips.

We used sales data, delivery and pick-up data, and other business data from EMSI and interviews with business managers as inputs for the Simio model. Adoption rates per business followed the three S-curve scenarios in Figure 2. Table 3 describes how we scaled up the number of participating businesses and commercial centers for each year.

In Year Five, we added five additional commercial centers to Austin and Ohio, beyond the two commercial centers with detailed simulation models. These additional commercial centers have similar physical characteristics and business types to the modeled centers. Thus, we scaled the findings from the centers simulated to estimate car miles, number of cars, reduced CO_2 and car crashes for the five additional commercial centers.

Reduced car use. Using the Simio simulation model, each scenario is evaluated for two cases: assuming only cars (no drones) provide pickup and delivery and then assuming both cars and drones together provide pickup and delivery. The vehicle miles saved are then calculated by comparing the car miles travelled for these two cases. The total number of cars reduced is calculated using the vehicle miles saved annually divided by the distance an average U.S. car travels annually, 11,500 miles.[11] The drone and no-drone cases also help us to calculate the percentage of pickup and delivery vehicle miles (or pickup and delivery cars on the road) that drones take over each year.

Previous drone delivery research and CO_2

While there has been a long-held assumption that drones could lower carbon emissions by reducing the number of delivery vehicles and consuming less energy than traditional trucks, there are only a few studies available that analyze this claim. They tend to show that, when traveling the same distance, drones will emit lower levels of CO_2 than other motorized vehicles. However, other studies have shown that drones tend to travel further distances per package delivery because they generally carry one package per trip. In contrast, alternative delivery methods may deliver multiple packages in a single delivery trip.[i]

The carbon savings of drone delivery is affected by carbon-emissions due to energy consumption (i.e. drone battery charging). One study shows that optimal reduction of CO_2 emissions by drone depends largely on the efficient energy consumption of drone charging stations, the source of electricity used, and the distances traveled per delivery. To take full advantage of drone environmental benefits, the authors of the study suggest locating drone distribution centers in close proximity to service areas, which is the "last mile" approach examined in this research.

An important consideration is that drone charging facilities can operate independently of the public utility grid, through alternative energy sources such as solar or wind. In this case, the CO_2 emissions for operating a drone charging facility are eliminated.

Reduced carbon emissions. The vehicle miles saved are also used to calculate the reduction in car CO_2 emissions through the adoption of drones. The CO_2 emissions required to charge the drone batteries are estimated by drawing on local utility emissions data for each of the MSA. The drone charging emissions are subtracted from the saved car emissions to estimate the overall savings in carbon emissions. A drone charging facility operating off the grid with renewable sources would lower emissions further, although the additional emission reduction would be negligible compared to the aggregate emissions reduction from fewer vehicle miles or cars on the road. The CO_2 emissions reduced are also expressed as equivalent acreage of forest, and the conversions are described in the appendix.

The model does not account for the effects of weather on drone energy usage. It is assumed that drones are using the optimal amount of energy when in flight, will stay in-flight throughout the entire delivery (pickup and delivery), and will take the most direct route for delivery.

Improved safety. Safety is another potential benefit of drone delivery. We estimated the number of car crashes avoided through the use of drone delivery based on the reduction in car miles for each scenario and commercial center in Year Five. Based on 2017 state data, cars are assumed to experience between 1.49 to 2.54 crashes per one million miles depending on the MSA, with additional details provided in the appendix.

In the following 'Results' section, we present an overview and table of results for each metropolitan area. The following 'Comparison' section includes a comparative analysis of the three metropolitan areas as well as feedback from business and government interviews.

Results by metropolitan area

Drone delivery in Christiansburg, Virginia – lower density

Context. We chose Christiansburg, Virginia, as a low-density, rural metropolitan area. It is a growing metropolitan area, and 62% of its housing is single-detached buildings with yards. Most of the businesses located in this metro area are clustered around certain main streets and highways, while residential areas are further away on tertiary roads. As such, the distance between delivery businesses and destination residences may be longer. Christiansburg is located in southwest Virginia, on the outskirts of the Appalachian Mountains, and about 45 minutes east of the West Virginia border.

Analysis. We simulated a five-mile commercial hub with a drone base in Christiansburg's major shopping district for Years One and Three. For Year Five, we added an additional commercial hub in Blacksburg, an adjacent town that includes Virginia Tech. If businesses and their customers were to use drone delivery, the impacts over five years are summarized in Table 4.

Table 4: Annual impact of drone delivery in Christiansburg, VA

	YEAR ONE	YEAR THREE	YEAR FIVE
	Consumers who use drones recover $2.2 million in time savings per year.	Consumers who use drones recover $12.4-20.5 million in time savings per year.	Consumers who use drones recover $23.0-45.9 million in time savings per year.
	Participating businesses keep up with the annual increases of 10.5% in e-commerce.	Participating retail businesses gain $21-82,000 in additional sales per year. Participating restaurants gain $26-62,000 (full-service) and $63-152,000 (limited-service) in additional sales per year.	Participating retail businesses gain $25-73,000 in additional sales per year. Participating restaurants gain $38-71,000 (full-service) and $94-174,000 (limited-service) in additional sales per year.
	Communities save 1.9 million miles per year in avoided travel across one commercial center, equivalent to 165 cars off the road (including 1.9% of all delivery and pickup cars).	Communities save 6.3-9.1 million miles per year in avoided travel across one commercial center, equivalent to 550-791 cars off the road (including 8.9-9.1% of all delivery and pickup cars).	After adding one additional commercial center, communities save 18.7-30.5 million miles per year in avoided travel across two commercial centers, equivalent to 1,622-2,653 cars off the road (including 13.5-14.5% of all delivery and pickup cars).

Communities save 738.3 tons of CO_2 per year in one commercial center, equivalent to 295.3 acres of new forest.	Communities save 2.4-3.4 thousand tons of CO_2 per year in one commercial center, equivalent to 1.0-1.7 thousand acres of new forest.	After adding one additional commercial center, communities save 7.2-11.7 thousand tons of CO_2 per year across two commercial centers, equivalent to 2.9-4.7 thousand acres of new forest.

By Year Five, communities could avoid as many as 28-46 car crashes per year with drone delivery.

Chris: A single working professional. In Christiansburg, Chris will save 194 hours per year with drone delivery.

Taylor: A parent of two young children. In Christiansburg, Taylor will save 97 hours per year with drone delivery, and may be able to provide his/her kids with healthier food options.

Darcy: A college student. In Christiansburg, Darcy will save 48 hours per year with drone delivery.

Ari: An elderly person living in a local nursing home. In Christiansburg, Ari will save 24 hours per year with drone delivery. Drones also improve Ari's food security and ability to adhere to prescription drugs, improving health outcomes.

Figure 7: Time savings by customer type in Christiansburg

Drone delivery in Austin, Texas – medium density

Context. We chose Austin, Texas, as a mid-density metropolitan area. In this large and growing metropolitan area, 61% of housing is single-detached buildings with yards. Similar to Christiansburg, businesses in Austin tend to cluster, particularly along major US routes and highways. As such, distances to residential areas may be greater. Located in central Texas, Austin is the capital of Texas.

Analysis. For Years One and Three, Virginia Tech researchers assumed a drone base is placed in two five-mile commercial centers located in the areas of Cedar Park and Crestview. For Year Five, we added five additional commercial centers with drone bases: Bastrop, Circle Ranch, Georgetown, Round Rock, and Taylor. If businesses and their customers adopt drone delivery, the expected impacts over five years are summarized in Table 5.

Table 5: Annual impact of drone delivery in Austin, TX

	YEAR ONE	YEAR THREE	YEAR FIVE
	Consumers who use drones recover $4.8 million in time savings per year.	Consumers who use drones recover $32.8-55.1 million in time savings per year.	Consumers who use drones recover $323.6-582.5 million in time savings per year.
	Participating businesses keep up with the annual increases of 10.5% in e-commerce.	Participating retail businesses gain $59-233,000 in additional sales per year. Participating restaurants gain $53-127,000 (full-service) and $104-249,000 (limited-service) in additional sales per year.	Participating retail businesses gain $72-208,000 in additional sales per year. Participating restaurants gain $79-145,000 (full-service) and $154-284,000 (limited-service) in additional sales per year.
	Communities save 1.7 million miles per year in avoided travel across two commercial centers, equivalent to 144 cars off the road (including 0.6-1.9% of all delivery and pickup cars).	Communities save 13.2– 23.9 million miles per year in avoided travel across two commercial centers, equivalent to 1,147-2,075 cars off the road (including 8.5-11.5% of all delivery and pickup cars).	After adding the five additional commercial centers, communities save 145.2-294.0 million miles per year in avoided travel across seven commercial centers, equivalent to 12,628-25,565 cars off the road (including 11.1-13.6% of all delivery and pickup cars).

	Communities save 645.4 tons of CO_2 per year in two commercial centers (equivalent of 258.2 acres of new forest)	Communities save 5.1-9.3 thousand tons of CO_2 per year in two commercial centers (equivalent of 2.1–3.7 thousand acres of new forest)	After adding the five additional commercial centers, communities save 56.1-113.9 thousand tons of CO_2 per year in seven commercial centers (equivalent of 22.7-46 thousand acres of new forest)
	By Year Five, communities could avoid as many as 287-580 car crashes per year with drone delivery.		

Chris: A single working professional. In Austin, Chris will save 203 hours per year with drone delivery.

Taylor: A parent of two young children. In Austin, Taylor will save 101 hours per year with drone delivery and may be able to provide his/her kids healthier and more diverse food options.

Darcy: A college student. Darcy will save 51 hours per year with drone delivery.

Ari: An elderly person living in a local nursing home. In Austin, Ari will save 25 hours per year with drone delivery. Drones also improve Ari's food security and ability to adhere to prescription drugs, improving health outcomes.

Figure 8: Time savings by customer type in Austin

Drone delivery in Columbus, Ohio – higher density

Context. We chose Columbus, Ohio, as our higher-density metropolitan area. In this large and growing metropolitan area, 64% of housing is single-detached buildings with yards. While Columbus only has slightly higher population density than Austin, its urban environment is distinctly different. Columbus businesses are more evenly distributed throughout the metro area, allowing for greater proximity (i.e. less distance) to residential areas. Columbus is located in central Ohio, where the Appalachian Mountains recede to meet the Midwestern Plains and Great Lakes regions.

Analysis. For Years One and Three, Virginia Tech researchers assumed a drone base is placed in two five-mile commercial centers located in the areas of Dublin and Whitehall. For Year Five, we added five additional bases surrounding Columbus' ring road, the I-270 express loop: Delaware, Grove City, Lancaster, Newark and Westerville. All commercial centers except for Westerville had similar built environments and densities to Dublin. If businesses and their customers were to use drone delivery, the impacts over five years are summarized in Table 6.

Table 6: Annual Impacts of drone delivery in Columbus, OH

	YEAR ONE	YEAR THREE	YEAR FIVE
	Consumers who use drones recover $3.1 million in time savings per year.	Consumers who use drones recover $22.3-37.6 million in time savings per year.	Consumers who use drones recover $219.8-403.8 million in time savings per year.
	Participating businesses keep up with the annual increases of 10.5% in e-commerce.	Participating retail businesses gain $28-109,000 in additional sales per year. Participating restaurants gain $36-87,000 (full-service) and $64-154,000 (limited-service) in additional sales per year.	Participating retail businesses gain $34-97,000 in additional sales per year. Participating restaurants gain $54-99,000 (full-service) and $95-176,000 (limited-service) in additional sales per year.
	Communities save 910 thousand miles per year in avoided travel across two commercial centers, equivalent to 79 cars off the road (including 0.4-2.3% of all delivery and pickup cars).	Communities save 9.5-13.9 million miles per year in avoided travel across two commercial centers, equivalent to 822-1,205 cars off the road (including 6.8-9.1% of all delivery and pickup cars).	After adding the five additional commercial centers, communities save 95.8-183.2 million miles per year in avoided travel across seven commercial centers, equivalent to 8,333-15,932 cars off the road (including 9.4-10.7% of all delivery and pickup cars).

	Communities save 341.1 tons of CO_2 per year in two commercial centers (equivalent of 136.5 acres of new forest)	Communities save 3.6–5.3 thousand tons of CO_2 per year in two commercial centers (equivalent of 1.4– 2.1 thousand acres of new forest)	After adding the five additional commercial centers, communities save 36.5-69.9 thousand tons of CO_2 per year in seven commercial centers (equivalent of 14.6–27.9 thousand acres of new forest)
	By Year Five, communities could avoid as many as 244-466 car crashes per year with drone delivery.		

Chris: A single working professional. In Columbus, Chris will save 214 hours per year with drone delivery.

Taylor: A parent of two young children. In Columbus, Taylor will save 107 hours per year with drone delivery and may be able to provide his/her kids healthier and more diverse food options.

Darcy: A college student. In Columbus, Darcy will save 54 hours per year with drone delivery.

Ari: An elderly person living in a local nursing home. In Columbus, Ari will save 24 hours per year with drone delivery. Drones also improve Ari's food security and ability to adhere to prescription drugs, improving health outcomes.

Figure 9: Time savings by customer type in Columbus

Comparison of results

This research explored three potential beneficiaries of drone delivery services: individual consumers, local businesses, and the broader community and environment. Individual consumers are able to save time by obtaining products quickly. Businesses who choose to adopt the technology are able to increase their customer reach and generate additional sales. The community benefits from reduced vehicle traffic and CO_2 emissions, as well as greater access to goods that could support long-term quality of life outcomes. Benefits vary by municipal region and are contingent on multiple factors.

1. Impact to consumers

Benefits to individuals varied based on density, mobility, congestion and cost of living. Assuming businesses and consumers adopt drone delivery at a rate along one of the three S-curves, by Year Five:

- **Service and access.** Drone delivery can serve 49-54% of people in each MSA, many of whom could not previously access rapid delivery services for a wide range of local businesses at a competitive price. Drone delivery can serve up to 3,381-66,087 individuals in each MSA (3.6-6.6% of total MSA residents) who do not have access to a car.

- **Time savings.** Consumers living in less densely populated areas with further distances to travel will benefit most from time savings. They will directly recover 31.5-56.7 hours of time annually (averaged across all residents) because they will not have to drive to pick up orders or wait for orders to be delivered. Those in more densely populated metropolitan areas will recover fewer hours annually.

- **Value of time.** However, when factoring in population and often cost of living, greater dollar benefits go to those in more populated areas. For example, in Year Five, for Austin, per person time savings could be:

  - 26.5-53.8 hours annually in less densely populated areas (e.g. Cedar Park); and
  - 15.2-30.0 hours annually in more densely populated areas (e.g. Crestview).

  However, total consumer time savings for individuals in the delivery zone of drones would be:

  - $71.3-$144.7 million in less densely populated areas (e.g. Cedar Park); and
  - $87.8-$173.8 million in more densely populated areas (e.g. Crestview).

Benefits differ by type of consumer

Consumer benefit can be further broken down by different types of consumers, as benefits will accrue differently based on the value of the service and individuals' propensity to adopt. The personas included in this report represent four common types of consumers who might benefit differently from drone delivery based on comfort with new technology, perceived free time available, mobility and income. While we did not quantify these varying benefits in monetary terms, this could be the subject of subsequent research and policy recommendations, especially as it relates to the use of this technology for social service purposes. For example, an infrequent user of drone delivery may still derive significant value from the service if they are otherwise immobile or have difficulty traveling.

Table 7: Consumer types and benefits from drone delivery

Consumer type	Tech savvy	Free time	Mobility	Income	Additional characteristics and benefits
A single working professional (e.g. Chris)	Varies	Low	High	High	Chris is an early adopter since delivery saves time to spend on working and socializing.
A parent with young children (e.g. Taylor)	Varies	Low	Low	Average	Taylor can save time to spend with family, and avoid the hassle of going to the store with small children.
An elderly person living in a local nursing home (e.g. Ari)	Varies	High	Low	Low	Ari is a late adopter to the technology. Ari is able to receive food and household essentials in a timely manner at an affordable price. Drone delivery can help Ari adhere to medications.
A college student (e.g. Darcy)	High	High	Average	Low	Darcy is an early adopter due to novelty, time savings, and the convenience of not driving.

Our interviews identified social applications for drone delivery

One example of a socially-oriented use of drone delivery is helping to support the work of Meals on Wheels programs across the U.S. Founded in Philadelphia, Meals on Wheels America is the leadership organization supporting more than 5,000 community-based food programs across the country that are dedicated to addressing senior isolation and hunger since 1954. This network of more than two million staff and volunteers delivers nutritious meals and conducts friendly visits and safety checks to nearly 2.4 million seniors (220 million meals) annually. Meals on Wheels focuses on caring for individuals whose limited mobility makes it hard to shop for food, prepare meals or socialize with others. Depending on individual circumstances, meals may be provided along a sliding fee scale, from no cost to full price. While no senior will be denied a meal because of an inability to pay, he/she may be asked to contribute voluntarily to the cost of a meal.[12]

The frequency of deliveries for these programs depends on a variety of factors, including number of staff/volunteers on call, the delivery distance, and the number of seniors on a particular route. For instance, the Meals on Wheels program in Columbus, Ohio has approximately 1,200 drivers (except for the 28 paid staff, all are volunteers), which allow them to serve 120 routes a day with 20 meals per route, and weekly delivery of 50 frozen meals per route. The vast majority of recipients are within a 25-mile radius of their Meals on Wheels headquarters, while the furthest are about 70-80 miles. Because of its rural nature, the Meals on Wheels program in Christiansburg, Virginia uses only paid drivers to serve 150 persons on six daily hot meal delivery routes.

Cost effectiveness can make drones a complementary solution for Meals on Wheels services. Drone delivery may be particularly useful for customers who are not conveniently located along a regular delivery route and are within the range of drone delivery. They can help to increase the volume and / or frequency of food deliveries, improving the quality of life for beneficiaries. However, while providing food is a major component of Meals on Wheels, human interaction with seniors plays a critical role in this program. Drivers who deliver food have conversations with often-isolated seniors, do small chores around the house (e.g. pick up mail), assess their wellbeing and will report back if something is amiss. For many seniors, this may be the only daily interaction they receive. Thus, drone delivery would work best as a complement to existing delivery methods.

2. Impact to local businesses

Benefits to individual businesses depend on the size of the stores (i.e. the annual sales). In both Christiansburg and Columbus, businesses had similar gains in store sales because their individual stores had relatively similar annual sales numbers. Average annual sales in these metro areas were about $3-4 million for retailers, $1 million for limited service restaurants, and $1.2-1.5 million for full-service restaurants. By comparison, Austin stores had significantly higher annual sales, between 150-200% larger average annual sales per store. As such, the aggregate value of additional e-commerce sales in Austin would be greater. Table 8 shows the annual revenue increase by geography in Year Five. The range accounts for the culture of delivery in the area, where residents in some commercial centers may order delivery more frequently that residents in other centers.

Table 8: Annual revenue gain due to drone delivery by type of business by Year Five

	Christiansburg and Columbus	Austin
Retail store	$25,000-97,000	$72,000-208,000
Full-service restaurant	$38,000-99,000	$78,000-145,000
Limited-service restaurant	$94,000-176,000	$154,000-284,000

Benefits differ by type of store

Many interviewed businesses expressed interest in drone delivery, citing the increased convenience and time saved for the customer, as well as the potential for increased store revenue. All agreed that drone delivery could reduce traffic on the road at least some extent and better support those who are homebound or do not want to drive. Stores that currently use third-party delivery services also saw drone use as safer and more efficient than current services. Many interviewees commented that drones could reduce the risk of misplacement or interference with the product.

Some store managers also expressed concerns about this new service. Certain stores emphasized the importance of face-to-face interaction with customers, which all delivery services in general eliminate. Retail stores and some restaurants explained that face-to-face interaction helped to understand the exact need of buyers and encourage impulse purchases. They see the interactive experience as part of their service. Others questioned the reliability of the technology and safety of the products delivered, which are common questions when incorporating new technology into daily life.

The adoption of drone delivery varies based on the type of business. According to store interviews, pharmacies, food services and a number of retail stores such as grocery stores or gift shops have more items weighing less than five pounds that could be delivered by drones. As e-commerce growth illustrates, some of the most attractive opportunities for retail delivery are groceries and clothing. About four out of eight grocery stores interviewed during this research indicated a significant enough proportion of customers making purchases of five pounds or less to warrant drone delivery. Grocery stores in more densely urban areas with higher numbers of young adults and elderly reported having a higher proportion of customers making small purchases. By comparison, grocery stores in more suburban areas reported a higher proportion of customers making larger orders, such as families with children.

Table 9 on the next page provides a preliminary typology of business types based on these qualitative interviews with businesses. Interviews identified possible example products, reasons for or against drone delivery adoption, and possible additional benefits cited by store managers and employees. Since these interviews, the imposition of COVID-19 restrictions has accelerated many of these trends.

Table 9: Different business types and benefits from drone delivery

Store type	Examples interviewed		Products under 5lbs	Drivers of adoption	Primary benefits
Retail	Local stores	Grocery Lifestyle Hardware Beauty Pharmacies Electronics Clothing Department	55%	The prospect of affordable on-demand delivery may drive adoption	Expand the reach of brick and mortar stores
	Chain stores			Higher product margins enable adoption and experimentation	Avoid warehousing costs
Restaurants	Full service		65%	The growth of demand for restaurant delivery, the existing cost of on-demand delivery and narrow product margins may drive adoption	Expand the reach and improve the utilization of the kitchen with complementary delivery services
	Limited service		75%		Expand the reach of existing restaurants

Our interviews identified pharmacy as an opportunity for drone delivery

Most pharmacy store managers and pharmacists interviewed saw clear benefits when considering the use of drones for the delivery of over-the-counter drugs, first aid, and toiletry products. Most customers of these stores only buy a few items, many of which could be delivered by drone. Even before the COVID-19 pandemic, pharmacists alluded to the importance of providing over-the-counter drugs to those with cold or flu without infecting others in their community. With the imposition of social distancing guidelines in 2020, contactless methods for obtaining cough suppressants, thermometers, and other pharmaceutical items is even more imperative.

Pharmacists wondered how the chain of custody for prescription drugs would be maintained if drones were to leave the prescriptions in the yard and customers were unable to immediately collect them. There may be no guarantee that the customer will retrieve the product immediately upon arrival. Particularly for certain classes of drugs such as opioids and stimulants, the relevant regulators will have to determine if and how this prescription drug transaction would be permitted with drone technology. However, one benefit of drone delivery is that it is timely and on-demand, meaning the customer is home when they place an order and when the product is delivered. Chain of custody may be ensured through app-based technology, e.g. by customers certifying their readiness for delivery prior to take-off. The potential impact to communities of drone delivery for prescription medication is explored below.

3. Impact to communities and the environment

Drone delivery benefits communities in a number of ways, including reducing vehicle miles traveled by road; reducing CO_2 emissions; reducing road accidents; and improving public health outcomes.

Benefits for road use and emissions differ by type of metropolitan area

Drone delivery can help to take cars off the road (both consumer vehicles picking up goods and delivery vehicles). In turn, this can help to reduce CO_2 emissions. Commercial centers with lower density would benefit more from drone delivery when considering the per trip or per person emissions. These areas tend to have a very concentrated commercial center with many stores, but their associated residential areas are almost completely separate and some distance away. For example, the commercial centers in Cedar Park, Texas; Dublin, Ohio; and Christiansburg, Virginia have a concentration of stores within a mall or a number of strip malls. They also have an assortment of superstores and some higher-end chains. However, these stores are within a concentrated center, while some of the residential neighborhoods they serve are 0.5-4 miles or more away.

By comparison, older neighborhoods closer to the urban center of a metropolitan area are often built on a grid pattern with closely-knit buildings. They tend to have stores and residential neighborhoods in close proximity to one another. Stores are located on main roads and corners of neighborhoods, but residential areas remain relatively proximate on the secondary roads. For example, the commercial centers in Crestview, Texas; Whitehall, Ohio; and Blacksburg, Virginia have neighborhoods and stores that are relatively interspersed with each other. While their sheer numbers of businesses and people have an overall larger effect on car miles and emissions, assuming high adoption rates, the per trip or per person car mile and CO^2 savings is lower. As such, unless there are distinctly higher adoption rates of drone delivery, less densely populated areas may see more benefits.

By reducing vehicle miles travelled by road, drone delivery can support better safety outcomes. Traffic safety relies on a complex set of variables. By Year Five, in a high adoption scenario, the presence of drone delivery improved traffic safety by 46-580 fewer car crashes per year due to fewer cars on the road. The number of lives saved annually depended on the current traffic fatality rates for each geography. Those with higher traffic fatality rates exhibited a greater impact from drone delivery.

Table 10 summarizes the other benefits of reduced vehicle travel and reduced CO_2 emissions per commercial center in Year Five by density.

Table 10: Community benefits in Year Five due to drone delivery (by commercial center)

	Lower density <2,000 people/mi^2 (e.g. Cedar Park, Texas and Christiansburg, Virginia)	**Higher density** >3,000 people/mi^2 (e.g. Crestview, Texas and Whitehall, Ohio)
Equivalent number of cars removed by drone delivery	1,600-6,600	983-8,300
Percent reduction in total delivery and pickup cars on the road due to drone delivery	12.2-15.0%	11.2-18.7%
Car miles saved per person	236-488	45-288
Annual CO_2 reduced (tons)	7,200-29,000	4,000-37,000
Annual CO_2 reduced (equivalent acres of forest)	2,900-12,000	1,700-15,000
Annual CO_2 reduced (equivalent number of trees in millions)	0.3-1.3	0.2-1.7

Benefits for healthcare depend on population size and vehicle ownership

The use of commercial drone delivery for prescription medications could have important public health benefits. While almost half of Americans are prescribed prescription drugs, not all prescriptions are picked up.[13] Primary medication nonadherence (PNA) occurs when "a new medication is prescribed for a patient, but the patient does not obtain the medication or an appropriate alternative within an acceptable period of time after it was prescribed." PNA includes written prescriptions that are never submitted to pharmacies and prescriptions that are submitted to pharmacies and never picked up.[14] Prescription abandonment is estimated at 3.27% nationwide.[15]

Prescription abandonment rates are influenced by out-of-pocket costs (18%), forgetting to submit a script (32%), and transportation issues (11%).[16] These barriers to adherence may be exacerbated by a patient's socioeconomic status. PNA was found to be higher among middle-to-low income patients. Economically disadvantaged patients also face transportation challenges, increasing the burden of commuting to and from pharmacies. Indeed, neighborhoods with moderately low vehicle ownership saw PNA rates of 12.0%; those with low vehicle ownership had PNA rates of 18.9%.[17]

Pharmacies, patients, and communities as a whole face significant costs as a result of PNA. Pharmacies incur up to a $10 restocking cost for abandoned prescription. In 2008, 110 million prescriptions were abandoned in the U.S., resulting in $500 million in costs for pharmacies. Patients face much steeper PNA costs. A 2017 study analyzing the economic impact of nonadherence across 14 disease groups found that patients face between $949-$44,190 (2015 dollars) in annual costs stemming from nonadherence. Furthermore, nonadherence to prescription medications has a negative effect on society, with deferred treatment leading to higher rates of disease among community members and increased burden on social workers, hospitals and publicly-funded community health clinics.

Table 11 provides estimates of abandonments for each of the five modeled commercial centers based on national trends. Abandonments are calculated as a percentage of population, so areas with higher populations had higher number of abandonments. Additionally, different age groups use prescription drugs at different frequencies. Up to 85% of individuals in the 60 and above age group, for instance, are estimated to take prescription drugs annually while only 22.5% of those aged between 0-20 are estimated to take prescription drugs. Estimates for abandonment are therefore influenced by age demographics in the area.

Table 11: Overall estimated prescription abandonment in commercial centers for Years One to Three (2017 data)

	Montgomery County, Virginia	Austin, Texas		Columbus, Ohio	
		Cedar Park	Crestview	Dublin	Whitehall
Total users of prescription medication	41,057	109,393	193,479	130,874	147,430
Overall abandonment (3.27%)	1,343	3,577	6,327	4,280	4,821
Total impact of abandonment (millions)	**$1.3-59.3**	**$3.4-158.1**	**$6.0-279.6**	**$4.1-189.1**	**$4.6-213.0**

Table 12 on the next page details abandonments as a result of low or no vehicle ownership in the modeled commercial centers. Abandonment rate is closely affected by the proportion of households without vehicle access, and drone delivery could provide significant benefits by helping these individuals to obtain their prescription medication.

Table 12: Estimated households and individuals with no vehicle access that could benefit from drone delivery

	Montgomery County, Virginia	Austin, Texas		Columbus, Ohio	
		Cedar Park	Crestview	Dublin	Whitehall
Total households	35,577	82,679	165,782	110,970	138,621
Households with no vehicle access	1,928	1,798	11,942	3,588	12,628
Estimated individuals with no vehicle access	3,381	3,364	20,351	4,628	31,500
Total users of prescription medication	1,549	1,540	9,321	2,120	14,427
Estimated individuals with no vehicle access who abandon prescriptions (18.9% of total prescription users)	**293**	**291**	**1,762**	**401**	**2,727**

Policy implications

While this research illustrates the potential benefits of drone delivery, integrating this technology seamlessly into local communities will require thoughtful collaboration between government and industry.

The impacts of drone delivery are affected by government policy

The FAA oversees the development and implementation of drone operations in the national airspace system. Through the FAA's Unmanned Aircraft Systems Integration Pilot Program (IPP), government and private entities have worked together to test how to integrate drone operations in the national airspace and local communities.[18] As the program comes to an end in 2020, industry, communities and governments alike have questioned what policies will be put in place for drone integration on a long-term basis.

These factors will affect the potential benefits of drone delivery. Without social acceptance, drone delivery is unlikely to experience high adoption. Likewise, if policy settings inhibit drone operations at scale, drone delivery is unlikely to meet customer and business expectations for service coverage, timeliness and price.

For example, in our interviews, a number of local policymakers raised questions about local authority over drones. Likewise, several local officials also discussed how zoning policies may be used to regulate the location of take-off and landing sites. By comparison, industry stakeholders discussed the benefits of harmonized federal regulation and suggested that zoning can have unintended consequences if used for exclusionary purposes.

To achieve the benefits described in this report, governments at all levels will need to ensure that policy measures are carefully designed to protect the public interest while enabling industry to offer viable services.

Industry and government need to collaborate for social acceptance

Interviews with both local businesses and local government emphasized the importance of responsible operations for social acceptance. For example, some operators are working with local governments to assess the placement of drone bases in commercial or industrial areas. Several companies continue to work on reducing the sound of their drones in flight. The sound from a drone may be high pitch and unfamiliar in a residential setting. Similarly, companies are also developing ways to reduce exposure to drone noise, such as by distributing their flight paths to minimize repeated overflights.

Public education is another important tool to promote social acceptance. In our interviews, local officials referred to the need for public education campaigns around drones and similar technology. Upon entering a community, drone operators should work closely with local government and other stakeholders to raise awareness of safety, responsible flying, and the value of drones to the community. In each of the metropolitan areas examined—Christiansburg, Virginia; Austin, Texas; and Columbus, Ohio—government officials recommended, and had previously participated in, education campaigns for new technologies or policies. For example, in Austin, the City of Austin works regularly with University of Texas faculty to examine how they might integrate new smart technology into different kinds of neighborhoods across the metropolitan area. In Christiansburg, the drone delivery service Wing has worked with local governments and nonprofits to engage the public at festivals, fairs and other "town hall" events.

Conclusion

This report measures the potential impact of drone delivery for consumers, local businesses and communities across the United States. By examining three metropolitan areas of different sizes, it illustrates the benefits of drone delivery and the demographic, geographic, technical and policy conditions necessary to realize those benefits.

Drones can be integrated into the larger transportation system and complement existing delivery models. They can enable rapid and on-demand deliveries to consumers across the "last mile"; help businesses to generate new sales; reduce road use, emissions and accidents; and help to promote better public health outcomes. Particularly in light of social distancing, drone delivery can play a major role in supporting rapid, cost-effective and contactless delivery for many on-demand goods.

The magnitude of these benefits depends on the geographic and population density of the given community, such as the distance between stores and residences. If the distance is greater, such as in Christiansburg Virginia, consumers may benefit more from drone delivery through time saved – as much as 23-45 hours of time saved annually per person. Likewise, in more densely connected communities, consumers may benefit more from the *value* of time saved – as much as $87.8-173.8 million in total time savings for residents in Crestview (Austin, Texas).

Meanwhile, businesses adopting drone technology would benefit from expanding their number of addressable customers and offering faster delivery services, all of which would boost sales. For retail stores, annual increases in revenue by Year Five could be between $25,300-208,200. By Year Five, full-service restaurants could gain $38,300-144,700 in additional annual revenue, and limited-service restaurants could gain $94,200-284,300 in additional annual revenue.

Communities may also benefit from fewer cars on the road (e.g. 1,600-25,600) and less CO_2 emissions (e.g. 7.2-113.9 thousand tons) each year. In highly congested areas, even the smallest decrease in vehicles could significantly reduce traffic, generating time savings for all residents in the area, not just consumers. Reduced miles driven on the road may result in fewer accidents, considering the high level of safety required of commercial drone delivery operations. Further, drone delivery could benefit demographics who are homebound or do not have easy access to transportation. For instance, residents may benefit from improved access to their prescription drugs, ensuring better adherence to medication plans and better overall health outcomes.

With these benefits and limitations in mind, business and government should consider how best to integrate drone technology into the everyday life of communities. Policy implications of this research include the importance of ongoing public education campaigns about safe and responsible drone operations, and ensuring that policy settings protect the public interest while enabling viable drone delivery operations at scale.

Appendix A: Simulation methodology

The Virginia Tech team developed a discrete event simulation model (using Simio software) to evaluate the use of drones for delivery for the three adoption storylines: (1) e-commerce only, (2) moderate drone boost, and (3) high drone boost. Each of these storylines are evaluated for Year 1, Year 3, and Year 5.

The customer demand for each business is estimated based on business interviews. For those businesses not interviewed, the customer demand was estimated based on annual sales and the number of orders for similar businesses. The percent of deliveries follows from our finding in the business interviews.

In the simulation, orders are generated and randomly assigned to each business based on their demand. We assume customers come from within a five-mile radius around the commercial centers. Within this radius, neighborhoods are used to represent potential delivery locations. The number of customers at each neighborhood or delivery location is approximated from population density data found in the U.S. Census' 2017 Five-Year American Community Survey. In the simulation, the customer for each order is assigned randomly to a neighborhood, based on population density.

A drone or car transports each order in the simulation. The model assumes sufficient cars and drones are available to support consumer demand. Businesses that adopt drones will prioritize use of drones for deliveries. Determining the optimal number of drones for each five-mile commercial center is beyond the scope of this work, but should be considered for future work.

The model assumes that delivery cars are in the business areas. When a retail store or restaurant receives an order, a nearby delivery car picks up the order and transports it to the consumer location. The order is assumed to be ready when the delivery car arrives. Following delivery, the car departs the neighborhood and returns to a business area. Car travel speed is dictated by the road segments travelled.

For drone delivery, the model assumes a drone departs the nest and travels to the retail store or restaurant to pick up an order. The order is assumed to be ready when the drone arrives. The drone then delivers the order to the consumer location. Following delivery, the drone returns to the nest. Drones are assumed to travel on average 65 miles per hour using a Pert distribution.

Using the Simio simulation model, each scenario is evaluated for two cases: assuming only cars (no drones) provide pickup and delivery and then assuming both cars and drones together provide pickup and delivery. For each scenario, the simulation is run for five replications and metrics are calculated from the average of these runs. The results from the simulation model are used to evaluate: (1) the number of customer orders completed, and whether they are completed by car or drone; (2) the number of miles travelled by cars and drones; (3) the estimated time to complete a customer order.

When reporting results, the Virginia Tech team assumes the following conversions:

1. Cars travel 11,500 miles per year on average.[19]

2. Cars emit 400 CO_2 grams/car mile (assuming 4.6 CO_2 tons per car year*1,000,000 grams per ton/11,500 miles per car year = 400 CO_2 grams/car mile).[19]

3. 1 metric ton of CO_2 is consumed by 45.929 trees per year (assuming 1 tree consumes 48 CO2 lbs per year*2204.62 lbs per ton = 45.929 trees/CO_2 ton per year).[20]

4. Drones are assumed to be responsible for 67.3 to 100.95 CO_2 grams per drone trip in Virginia and Ohio. Virginia and Ohio are served by American Electric Power (AEP). AEP reports CO_2 equivalent emissions of 673 grams/kWhrs. Wing reports 0.1 – 0.15 kWhrs are consumed per drone trip. Thus, the team evaluated a range of 67.3 to 100.95 CO_2 grams per drone trip in Virginia and Ohio.[21]

5. Drones are assumed to be responsible for 38.77 to 58.16 CO_2 grams per trip in Austin, Texas. AustinEnergy report reports 853 lbs CO_2 emissions per MWhrs. With 2204.62 lbs per metric ton and 1000kWhrs per MWhr, this converts to 387.7 grams/kWhr. Wing reports 0.1 – 0.15 kWhrs are consumed per drone trip. Thus, the team evaluated a range of 38.77 to 58.16 CO_2 grams per drone trip in Austin, Texas.[22]

6. Based on 2017 state data, cars are assumed to experience the following crash rates in each of the states studied:

    a. 1.49 crashes per one million miles in Virginia[23];
    b. 2.54 crashes per one million miles in Ohio[24]; and
    c. 1.97 crashes per one million miles in Texas.[25]

7. One acre of new forest sequesters approximately 2.5 tons of carbon annually.[26]

Appendix B: Metropolitan area descriptions

Below are descriptions of the three metropolitan areas in this study, which provide greater detail and context as to why these metropolitan areas were chosen for modeling.

Christiansburg, Virginia

The Christiansburg metropolitan area is a low-density MSA located in southwest Virginia, on the outskirts of the Appalachian Mountains, and about 45 minutes east of the West Virginia border. It is a prime case for drone delivery in low-density cities for several reasons.

This MSA is home to Virginia Tech, which equates to a younger population. The region's population continues to grow at a rate of 1% annually. Population growth is primarily concentrated in the early 20s and mid-30s age cohorts. For Christiansburg, population density remains relatively low at 170 people per square mile, making it difficult to obtain food or goods rapidly. About 62% of housing units are detached houses with yards, enabling delivery by drone.

The MSA includes four counties with several small towns containing fewer than 10,000 people. Blacksburg, Christiansburg and Radford are the three largest incorporated municipalities with greater than 10,000 inhabitants. Christiansburg is the county seat of Montgomery county. It has a small downtown area and a larger commercial center with superstores closer to the highway. This commercial center is one of the major shopping locales for many residents in southwest Virginia and is located between Virginia Tech and Radford University. However, as the commercial center serves so many in the region, congestion along the connecting highways (US 114, US 460, and I-81) has historically been a challenge. The area continues to grow in terms of commercial stores and housing developments, and plans are in motion for future road improvements.

Autonomous vehicles—air, ground, and sea—are technologies that state and local governments in this area want to support. The first FAA-certified drone air carrier, Wing, commenced operations in Christiansburg in 2019. The region hosts several businesses specializing in unmanned systems technology, and it has supported the development of a regional chapter of the Association for Unmanned Vehicle Systems International. Virginia Tech has supported this growth through unmanned systems research, which facilitated the development of the Mid-Atlantic Aviation Partnership (MAAP), one of six FAA-designated test sites for unmanned aircraft systems in the U.S.

Austin, Texas

The Austin metropolitan area is considered a large MSA, with a population of 2,000,590 people. However, the MSA has a lower population density compared to many of its peers, with 474 people per square mile. Located in central Texas, Austin is the capital of Texas and home to the University of Texas System's flagship institution. Austin has experienced recent population growth of 9% between 2014 and 2017, and is expected to continue that growth trend in the coming years. Finally, 61% of the MSA's housing stock is detached housing. Primary industries include government, higher education, business and IT services, as well as a growing tourism and cultural industry.

The Austin MSA is comprised of five counties, each with over six dozen incorporated and unincorporated communities. The region has nine cities with populations of 20,000 or more. The City of Austin is at the center of this region and is connected through a large network of highways. Austin is consistently ranked among America's most congested metropolitan areas, presenting a unique opportunity to improve quality of life by reducing congestion and reducing the amount of time for consumers to obtain goods. In 2019, the city was ranked 18th in worst U.S. traffic, with 69 hours per capita and $1,021 per driver lost due to congestion.[27] Austin has shown commitment to improving congestion, with recent years decreasing congestion hours, narrowing congestion times between peak and non-peak hours, and improving the reliability of time traveled on roads.[28]

For further analysis, researchers chose two five-mile commercial centers, both with 50% or more single detached housing. The first is Crestview, a neighborhood of Austin, just north of its downtown. Various retail establishments are located around the boundaries of Crestview and other surrounding neighborhoods. Prominent stores include Walmart, two Walgreens pharmacies, and retailer H.E.B. Plus, alongside a number of popular restaurants and smaller retail outfits. The second area, Cedar Park, is a major suburb just northeast of Austin. The Anderson Mill, Riviera and Cypress Hill neighborhoods of Cedar Park are connected by one core commercial center. Nearby retail stores include Target, Walmart, Sam's Club, H.E.B. Plus, Home Depot, and Lowes. The Lakeline Mall is also central to these neighborhoods, hosting a variety of clothing-oriented retail stores. For Year Five, Virginia Tech researchers added five additional commercial hubs: Bastrop, Circle Ranch, Georgetown, Round Rock, and Taylor. All but Circle Ranch, a planned community in southeast Austin, are incorporated communities just outside Austin.

Beyond demographic and spatial factors, there are other reasons why Austin may be a promising candidate for drone delivery. First, Texas is a growing IT industry hub and tends to be open to new opportunities. Its transportation planning department has taken the lead in identifying new technology and new approaches to decrease traffic congestion and increase overall quality of life for metropolitan residents. Drones are becoming more commonplace in police searches, mapping and firefighting. Drone research is also underway at the University of Texas, most notably in agricultural and wildlife conservation applications. Additionally, like MAAP at Virginia Tech, Texas is collaborating with the FAA as a designated test site for drone integration via the Lone Star UAS Center of Excellence and Innovation.

Columbus, Ohio

As the final metropolitan area for this research, Columbus is denser overall, but has a more even distribution of retail and restaurant businesses across its MSA than Austin, Texas. Columbus is located in central Ohio, where the Appalachian Mountains recede to meet the Midwestern Plains and Great Lakes regions. The capital of Ohio, Columbus is in the top 50 most populated metropolitan areas and is home to The Ohio State University. As such, it is a center of government, education, and culture.

Columbus is amenable to drone delivery due to its population growth, low density, and large proportion of detached housing in a number of neighborhoods both inside Columbus proper as well as the surrounding area. Between 2014 and 2017, the MSA population grew by 4% and is expected to maintain that growth rate for the coming five years. The MSA's low population density of 510 people per square mile and high percentage of detached houses (64%) makes the region a prime candidate for drone delivery. Primary industries include government, higher education, financial and insurance services, as well as distribution, transportation, and logistics.

Comprised of nine counties, the Columbus MSA has more population centers compared to the two other metropolitan areas in this research. The center of the MSA is the larger city of Columbus with a dense downtown area for government, finance, and Ohio State University. On a grid street pattern, the city is surrounded by older 19th and 20th century neighborhoods and an express loop highway (I-270). The metropolitan area has over thirteen smaller townships and cities on its outskirts. Columbus is another congested city, ranking 27th among U.S. cities, with 43 hours per capita and $636 per driver lost due to congestion.[29]

In order to select the best commercial centers for our analysis, we avoided the downtown area, with its larger and more densely populated buildings, in favor of the surrounding suburbs with 50% or more single, detached housing. For Years One and Three, we chose the City of Whitehall, an enclave of Columbus and just inside the I-270 express loop. Whitehall has hosted a Fedex distribution center since 2009, which serves North and East Columbus. As e-commerce has increased, so has the congestion in Whitehall. The Fedex location has grown from 250 to 600 employees since 2009.

The second commercial center chosen for Years One and Three was Dublin, Ohio. Located on the northwest portion of the I-270 express loop, the Dublin area serves as the headquarters of large corporations such as Ashland Incorporated and Wendy's International. Dublin has many commercial centers ranging from a walkable main street to the far more congested Sawmill Road with superstores. For Year Five, Virginia Tech researchers added five additional commercial hubs, mostly outside the I-270 express loop: Delaware, Grove City, Lancaster, Newark and Westerville. Other than Westerville, the other hubs are distinctly smaller than Dublin and Whitehall.

The autonomous vehicle industry is widely supported both in the state of Ohio, and in Columbus.

In 2013, Ohio establish a UAS center which "serves as the state's one-stop shop for unmanned aircraft and advanced aviation technologies".[30] In 2014, the Ohio General Assembly created the aerospace and aviation technology committee, which they charged with bringing together stakeholders across the aviation community to develop a unified strategy for promoting the sector. In 2016, Columbus won the first ever Smart City Challenge launched by the U.S. Department of Transportation. In recent years, the city has experimented with autonomous shuttles and other smart technology to improve the transportation environment. DriveOhio, a consortium of government, higher education and private industry, regularly works "to build Ohio's infrastructure for smart mobility." In 2018, DriveOhio and Ohio State researchers partnered to begin a three-year study on the use of drones to monitor traffic and roadway conditions along Ohio's 33 Smart Mobility Corridor, a stretch of highway which runs through Dublin.

Appendix C: Results by initial commercial centers

		Christiansburg, VA			Crestview, TX			Cedar Park, TX			Dublin, OH			Whitehall, OH		
		Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5
Population		79,117			333,164			154,667			206,238			248,928		
Population density (per square mile)		608.6			4,244.1			1,970.3			2,627.2			3,171.1		
Total number of businesses		189.0			402.0			225.0			278.0			215.0		
Total number of businesses that currently use delivery *pre-COVID-19		131.0			244.0			146.0			216.0			167.0		
Drones replace what % of total delivery miles / cars on road	**Low**	2.7%	9.1%	14.5%	1.9%	9.6%	15.9%	0.6%	8.5%	12.2%	0.4%	9.0%	11.8%	2.3%	6.8%	11.2%
	High	2.7%	8.9%	13.5%	1.9%	11.5%	18.7%	0.6%	10.2%	15.0%	0.4%	8.2%	12.7%	2.3%	9.1%	15.7%
Number of fewer cars due to drone (per year)	**Low**	164.9	549.9	1,622.1	97.8	486.4	3,973.5	46.6	661.1	2,783.9	33.8	689.1	3,438.2	45.5	132.5	983.0
	High	164.9	790.6	2,653.0	97.8	859.6	8,344.7	46.6	1,215.1	6,564.0	33.8	931.4	7,226.6	45.5	273.5	2,699.5
Car miles saved (millions)	**Low**	1.9	6.3	18.7	1.1	5.6	45.7	0.5	7.6	32.0	0.4	7.9	39.5	0.5	1.5	11.3
	High	1.9	9.1	30.5	1.1	9.9	96.0	0.5	14.0	75.5	0.4	10.7	83.1	0.5	3.1	31.0

		Christiansburg, VA			Crestview, TX			Cedar Park, TX			Dublin, OH			Whitehall, OH		
		Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5
CO_2 removed	Low	738.3	2,411.3	7,221.3	438.1	2,180.6	17,551.3	207.3	2,960.5	12,248.2	143.5	3,051.4	15,217.9	197.7	553.8	4,169.9
	High	738.3	3,448.2	11,715.1	438.1	3,863.9	36,929.9	207.3	5,459.4	29,057.0	143.5	4,094.3	32,002.6	197.7	1,166.6	11,696.5
Equivalent acres of trees	Low	295.3	964.5	2,888.5	175.2	872.2	7,020.5	82.9	1,184.2	4,899.3	57.4	1,220.6	6,087.2	79.1	221.5	1,668.0
	High	295.3	1,379.3	4,686.0	175.2	1,545.6	14,772.0	82.9	2,183.8	11,622.8	57.4	1,637.7	12,801.0	79.1	466.6	4,678.6
Equivalent number of trees	Low	33,908.3	110,753.8	331,680.2	20,123.1	100,154.3	806,141.3	9,520.3	135,977.0	562,566.8	6,590.3	140,152.3	698,968.5	9,078.3	25,437.7	191,526.5
	High	33,908.3	158,378.1	538,079.6	20,123.1	177,472.6	1,696,210.3	9,520.3	250,752.1	1,334,601.8	6,590.3	188,055.2	1,469,895.4	9,078.3	53,580.7	537,227.9
Car crashes Avoided	Low	2.8	9.5	27.9	2.2	11.0	90.2	1.1	15.0	63.2	1.0	20.2	100.6	1.3	3.9	28.8
	High	2.8	13.6	45.6	2.2	19.5	189.4	1.1	27.6	149.0	1.0	27.2	211.3	1.3	8.0	78.9
Consumer time savings ($ million)	Low	2.2	12.4	23.0	3.1	14.2	87.8	1.6	18.6	71.3	1.7	16.2	70.1	1.4	6.1	38.9
	High	2.2	20.5	51.1	3.1	23.9	173.8	1.6	31.2	144.7	1.7	26.9	145.0	1.4	10.7	79.3
Hours saved per person	Low	2.1	11.8	22.0	0.5	2.5	15.15	0.6	6.9	26.5	0.5	5.0	21.5	0.4	1.5	9.9
	High	2.1	19.7	48.9	0.5	4.1	30.0	0.6	11.6	53.8	0.5	8.3	40.4	0.4	2.7	18.3

		Christiansburg, VA			Crestview, TX			Cedar Park, TX			Dublin, OH			Whitehall, OH		
		Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5	Year 1	Year 3	Year 5
Additional revenue due to drones for participating retail business	**Low**	187,639	20,736	25,320	534,722	59,093	72,155	534,722	59,093	72,155	249,485	27,571	33,665	249,485	27,571	33,665
	High	187,639	81,840	73,076	534,722	233,223	208,247	534,722	233,223	208,247	249,485	108,815	97,162	249,485	108,815	97,162
Additional revenue due to drones for participating full-service restaurant business	**Low**	105,375	25,732	38,300	216,120	52,766	78,552	216,120	52,766	78,552	148,199	36,190	53,866	148,199	36,190	53,866
	High	105,375	61,706	70,568	216,120	126,557	144,732	216,120	126,557	144,732	148,199	86,784	99,247	148,199	86,784	99,247
Additional revenue due to drones for participating limited-service restaurant business	**Low**	259,408	63,348	94,286	424,534	103,671	154,304	424,534	103,671	154,304	262,590	64,125	95,443	262,590	64,125	95,443
	High	259,408	151,906	173,722	424,534	248,602	284,305	424,534	248,602	284,305	262,590	153,770	175,853	262,590	153,770	175,853

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