The Energy Implications of Drones for Package Delivery

A Geographic Information System Comparison

Timothy R. Gulden
Preface

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

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

The study includes several complementary research efforts focused on different facets of the delivery drone system and their likely impact on the public. In this report, we use a geographic information system analysis to compare truck versus delivery drone energy use.

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

- What’s the Buzz on Delivery Drones? (Welser and Xu, 2016)
- What’s the Buzz? The City-Scale Impacts of Drone Delivery (Lohn, 2017)
- Design Perspectives on Delivery Drones (Xu, 2017)
- Small Unmanned Aerial System Certification and Traffic Management Systems (Kuhn, forthcoming)
- International Commercial Drone Regulation and Drone Delivery Services (Jones, forthcoming).

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RAND Science, Technology, and Policy

The research reported here was conducted in the RAND Science, Technology, and Policy program, which focuses primarily on the role of scientific development and technological innovation in human behavior, global and regional decisionmaking as it relates to science and
technology, and the concurrent effects that science and technology have on policy analysis and policy choices. The program covers such topics as space exploration, information and telecommunication technologies, and nano- and biotechnologies. Program research is supported by government agencies, foundations, and the private sector.

This program is part of RAND Justice, Infrastructure, and Environment, a division of the RAND Corporation dedicated to improving policy- and decisionmaking in a wide range of policy domains, including civil and criminal justice, infrastructure development and financing, environmental policy, transportation planning and technology, immigration and border protection, public and occupational safety, energy policy, science and innovation policy, space, and telecommunications.

For more information about RAND Science, Technology, and Policy, see www.rand.org/jie/stp or contact the director at stp@rand.org.

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Summary

If drones are commonly used to deliver small packages to places suited for such delivery, they will not be responsible for all deliveries in a city; they will instead compete with the traditional trucks that are currently responsible for deliveries, with trucks handling larger items and difficult delivery situations. Because drones and trucks use different amounts of energy and are suited to very different routing strategies, this raises the question of how such a shift might be expected to change the overall energy consumption required for package delivery.

In this report, we provide a simple simulation of the total energy-use impact of shifting the most suitable (lightest total weight) 20 percent of the United Parcel Service (UPS) package delivery stops in Minneapolis from traditional UPS trucks to delivery drones. The reduced number of stops would allow for a smaller truck fleet delivering to fewer service areas. This preliminary study uses a very limited data set derived from a National Renewable Energy Laboratory (NREL) study of conventional and hybrid delivery vans in Minneapolis (Lammert and Walkowicz, 2012).

Our general approach was to digitize a route map in Minneapolis from the NREL study, characterize the delivery districts that it depicts, create a comparable set of districts covering a 10-mile radius from the center of the city, and calculate the miles driven and gallons of diesel required to deliver packages by truck to those districts. We then created a hypothetical set of delivery points within these districts and assigned 20 percent of those points to be serviced by drones, calculating the drone miles and energy required to make these deliveries. We then created a new set of zones to reflect the 20-percent fewer stops (that is, the fact that each truck can now serve an area containing 20-percent more people) and repeated the mileage and diesel consumption estimate for these areas. We then estimated the electricity required by the drones and expressed it in terms of its energy equivalent in diesel. Finally, we combined the estimated energy used by trucks and drones to produce an estimate of total energy consumption under the drone scenario.

We found that the 20-percent drone scenario would require 13 fewer truck routes, 468 fewer truck miles, and 46.8 fewer gallons of diesel fuel (assuming an efficiency of 10 miles per gallon [MPG], which is consistent with the NREL data). The drone delivery would involve 1,550 drone trips totaling 9,406 miles flown. Drones, however, are much lighter than trucks and thus take less energy to move—even in flight. Assuming a tilt-rotor fixed-wing design, other work in this project suggests a delivery drone fuel economy on the order of 460 MPGe (MPG equivalent), allowing all the drone deliveries to be conducted with the energy equivalent of 20.4 gallons of diesel. This results in a savings of the equivalent of 26.4 gallons of diesel for a net savings of about 5.7 percent when drones are used to cover 20 percent of the stops as compared with using trucks to make the same deliveries.
While the numbers and calculations in this preliminary study are rough, the analysis supports the idea that the energy requirements for truck and drone delivery for small packages are of the same order of magnitude and, thus, shifting some deliveries to drones would not have a major impact on the energy intensity of package delivery. However, it would shift this energy from diesel-burning trucks to electric drones, which might have a beneficial impact on the carbon footprint of package delivery until the delivery truck fleet can be converted to lower-carbon fuels.
This study benefited greatly from the input and discussion of the other members of the fiscal year (FY) 2016 Delivery Drones and the City project team—in particular, William Welser, Jia Xu, Andrew Lohn, Flavia Tsang, Kenneth Kuhn, Shira Efron, and Rebecca Balebako. The work also could not have happened without funding from the FY 2016 RAND-Initiated Research program, overseen by Susan Marquis and Howard Shatz. We are grateful to two reviewers who provided substantive and constructive comments: Richard Mason from RAND and Brian J. German from the School of Aerospace Engineering at the Georgia Institute of Technology. The report is both clearer and better for their input.
## Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<tr>
<td>MPG</td>
<td>miles per gallon</td>
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<tr>
<td>MPGe</td>
<td>miles per gallon equivalent</td>
</tr>
<tr>
<td>UAV</td>
<td>unmanned aerial vehicle</td>
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<td>UPS</td>
<td>United Parcel Service</td>
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Chapter One. Introduction

If delivery companies shift their delivery strategy to include autonomous unmanned aerial vehicles, commonly referred to as drones, it can be expected that they will use drones to deliver small packages, particularly to locations that are suited to such delivery. This would free trucks from the need to make stops with only small deliveries, allowing them to focus on larger items and difficult delivery situations. Drones and trucks are quite different with respect to their weight, energy needs, and optimal routing strategies. This raises the question of how such a shift might be expected to change the overall energy consumption required for package delivery.

In this report, we provide a simple simulation of the overall energy use impact of shifting 20 percent of the United Parcel Service (UPS) package delivery stops in Minneapolis from hybrid, but otherwise traditional, UPS trucks to delivery drones with specifications similar to those currently being tested by Amazon. We assume that the delivery company would choose which packages would be delivered by each mode, delivering small packages that are within range of the depot by drone and heavier and longer-distance deliveries by truck. We further assume, based on anecdotal information, that about 20 percent of deliveries would be appropriate for drone delivery (i.e., deliveries weighing 5 lbs or less). The reduced number of stops would allow for a smaller truck fleet delivering to fewer service areas. This preliminary study uses a very limited data set derived from a National Renewable Energy Laboratory (NREL) study of conventional and hybrid delivery vans in Minneapolis.

Organization of This Report

In Chapter Two, we provide a discussion of how we conducted the simulation and the energy analysis derived from the simulation. In Chapter Three, we provide some brief conclusions.
Chapter Two. Analyzing the Impact on Energy Use of Shifting Delivery Stops from Trucks to Drones

In this chapter, we analyze the impact on energy use of shifting the servicing of 20 percent of delivery stops from UPS delivery trucks to drones. We use data from an actual city by creating a simple simulation model and analyzing the change in energy use that the simulation suggests.

Approach to Simulation Modeling

We rely heavily on the NREL study *Eighteen-Month Final Evaluation of UPS Second Generation Diesel Hybrid-Electric Delivery Vans* to ground this report (Lammert and Walkowicz, 2012). The focus of the NREL evaluation was on Minneapolis, Minnesota.

Our general approach was to digitize a route map from the NREL study of Minneapolis, characterize the delivery districts that it depicts, create a comparable set of districts covering a 10-mile radius from the center of the city, and calculate the miles driven and gallons of diesel required to deliver packages by truck to those districts. We then created a hypothetical set of delivery points within these districts and assigned 20 percent of those delivery points to be delivered by drones, calculating the drone miles and energy required to make these deliveries. We then created a new set of zones to reflect the 20-percent fewer stops (that is, each truck can now serve an area containing 20-percent more people) and repeated the mileage and diesel consumption estimate for these areas. Finally, we compared the energy content of the diesel saved with the electricity used by the drones to find the energy consumption of the two delivery modalities. The remainder of this chapter describes this approach in detail.
Estimating Delivery Areas

Figure 2.1 shows a map that depicts Global Positioning System (GPS) traces for 13 delivery routes in the Minneapolis metropolitan area. While these routes cannot be said to be statistically representative of all routes nationally or even within this region, they were chosen by the NREL group to represent a reasonable mix of high- and low-density areas reflecting the general composition of routes in a metropolitan area.

Different routes are depicted in contrasting colors. We used ArcGIS to geo-register the map to the Minneapolis street network.

Figure 2.1. Estimating Delivery Areas in Minneapolis: Analyzing the NREL Map

Delivery districts were hand-digitized based on visual inspection. These areas are shown in black in Figure 2.2. Note that the routes do not tend to overlap except in the transit phase, during which the trucks drive from the depot to their respective delivery areas. This lack of overlap is consistent with a delivery strategy wherein each truck has responsibility for all deliveries within a contiguous geographic delivery region.

With the delivery areas approximated, we were able to calculate their areas. We also measured the “stem” driving distance—the distance from the depot (the red central dot in Figure 2.2) to the district—and found these measurements to be consistent with information published in the NREL report.

**Figure 2.2. Digitizing Delivery Areas from the Geo-Registered Map**

SOURCE: Lammert and Walkowicz, 2012, p. 9; modifications by RAND authors.
The digitized delivery areas shown in Figure 2.2 were then overlaid with block-level population data from the 2010 U.S. Census. Figure 2.3 shows the numbered digitized districts in black overlaid on 2010 census blocks colored by relative population density ranging from green (low) to orange (high). As in Figure 2.2, the depot is depicted by the central red dot. A 10-mile radius around the depot is shown by the black circle. The population from blocks that were partially within districts was allocated according to the percentage of the block falling within the district. The digitized districts were found to contain between 7,500 and 28,000 people, with no correlation between district area and population. This lack of correlation supports the idea that density and driving distance are not major determinants of driver workload: Package delivery makes up a majority of a driver’s workday. We therefore assume that district boundaries are drawn primarily based on the population that they contain. This assumption is used in subsequent steps to define a set of hypothetical delivery areas covering the metropolitan region.

Figure 2.3. Delivery Areas Overlaid with 2010 U.S. Census Block-Level Data

Next, we created a set of synthetic delivery districts using the ClusterPy library in the Python programming language. These districts are shown in contrasting colors in Figure 2.4. They are overlaid with the districts digitized from the report (numbered in black), the central UPS depot (red dot), and the 10-mile radius around the depot (the black circle). These areas have a target size of 13,400 people, with the algorithm tuned to produce some variation (mean: 13,381; minimum: 12,840; maximum: 19,689). This results in a set of 86 delivery areas required to cover a 10-mile radius from the UPS depot location in the center of the city. While these districts do not correspond precisely with the districts depicted on the map, they have similar properties of size, shape, and population density.

Figure 2.4. Synthetic Delivery Districts Derived from Block-Level Data
**Estimating Drone Stops**

Our next step was to estimate drone stops. Based on anecdotal reports, it appears that UPS residential delivery drivers generally make about 90 stops per day. Following this general rule, we scattered 90 stops randomly within each delivery district to simulate a total of 7,740 delivery locations. Figure 2.5 shows these stops in black overlaid on the synthetic delivery districts. Note that this analysis assumes constant population density within each district, while allowing population density to vary substantially from one district to another. In reality, there is also substantial variation in density within some districts; however, the assumption of constant density within districts preserves simplicity while maintaining sufficient fidelity for this analysis.

**Figure 2.5. Ninety Stops Scattered at Random Within Each Delivery Area**
From these 7,740 delivery points, we randomly selected 20 percent to be delivered by drones. These 1,550 points are shown in blue in Figure 2.6. The geodetic crow-flies distance from each point to the depot was calculated and this distance was doubled to reflect the round-trip flight distance, assuming one delivery per drone trip. These distances were summed across the whole city to produce an estimate of total drone miles flown to deliver to all the drone-designated stops.

It should be noted that these distances may be somewhat optimistic. Such factors as airspace restrictions, noise abatement zones, tall buildings, and major terrain features might require deviations from the great circle distance (GCD) shortest path. For the sake of simplicity, we will use GCDs, assuming that such deviations would not be required for most flight paths.

*Figure 2.6. Estimating Drone Stops as a Random 20 Percent of Stops*
**Redrawing Delivery Areas**

The next step is to redraw the delivery areas to reflect the reduced truck workload. With 20 percent of the delivery stops shifted to drones, each truck can now serve 20-percent more households and businesses. The synthetic delivery areas were recalculated to include an average of 16,000 people (up from the previous 13,400 people). This reduces the number of districts from 86 to 73. The resulting districts are shown in Figure 2.7.

![Figure 2.7. Redrawing Delivery Areas](image)

**Estimating Driving Distance**

With redrawn delivery areas, we next estimated driving distance. Other research in this project on a stylized version of the classic traveling salesman problem has shown that the driving distance ($D$) for a given number of stops (in this case 90 stops) grows with the square root of the delivery area ($A$): $D = \alpha \sqrt{A}$ (Lohn, 2017). This stands to reason because it reflects the more general relationship between an areal and linear feature (e.g., the area and diameter of a circle). Empirical analysis of the NREL data, regressing miles traveled in the delivery area against the square root of its area in square miles, suggests a constant $\alpha = 25$. This formula provides a
theoretically and empirically grounded estimate of the required driving distance that could be expected for a delivery area of a given size, thus letting us produce a credible estimate of driving distance for each synthetic delivery area without actually calculating optimal routing for every stop.

Results of the Energy Analysis

Having set up the simulation model, we then conducted the energy analysis to determine what effect shifting 20 percent of the delivery stops from UPS trucks to drones would have on energy usage. Table 2.1 shows the results of that analysis, highlighting the differences between the baseline, where all the deliveries are by UPS trucks, and the scenario we simulated, where 20 percent of the deliveries would be done by drones. Approximate truck miles driven can be calculated both for the baseline and for the scenario where there is a 20-percent shift to drones using the formula $D = 25\sqrt{A}$ plus the round trip “stem” distance of the route from the depot.

<table>
<thead>
<tr>
<th>Categories Analyzed</th>
<th>Baseline: 100 Percent Trucks/0 Percent Drones</th>
<th>Scenario: 80 Percent Trucks/20 Percent Drones</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck delivery areas</td>
<td>86 delivery areas</td>
<td>73 delivery areas</td>
<td>13 fewer truck delivery areas</td>
</tr>
<tr>
<td>Truck miles</td>
<td>4,596 miles</td>
<td>4,128 miles</td>
<td>468 fewer truck miles</td>
</tr>
<tr>
<td>Truck fuel use (10 MPG)</td>
<td>459.6 gallons</td>
<td>412.8 gallons</td>
<td>46.8 fewer gallons</td>
</tr>
<tr>
<td>Drone stops</td>
<td>0 stops</td>
<td>1,550 stops</td>
<td>1,550 more drone stops</td>
</tr>
<tr>
<td>Drone miles</td>
<td>0 miles</td>
<td>9,406 miles</td>
<td>9,406 more drone miles</td>
</tr>
<tr>
<td>Drone fuel use (450 MPG)</td>
<td>0 gallons (MPGe)</td>
<td>20.4 gallons (MPGe)</td>
<td>20.4 more gallons (MPGe)</td>
</tr>
</tbody>
</table>

NOTE: MPG = miles per gallon. MPGe = miles per gallon equivalent.

We found that the 20-percent drone scenario would require 13 fewer truck delivery areas, 468 fewer truck miles, and 46.8 fewer gallons of diesel fuel. This assumes that the delivery trucks use the hybrid design tested by NREL, where hybrid delivery trucks were found to achieve 10 MPG in real-world use, including idle time and time spent in traffic (Lammert and Walkowicz, 2012).

The drone delivery would involve 1,550 drone trips totaling 9,406 miles flown. Drones, however, are much lighter than trucks and thus take less energy to move—even in flight.

We assume a drone design similar to those demonstrated in 2016 by Amazon Prime Air. In complementary research in this series, Jia Xu (2017) examines these vehicles and develops a simulation model that generalizes their capabilities. These vehicles weigh about 55 lbs and can carry a 5-lb package to a delivery point within 10 miles of the depot (20-mile round trip). They use a hybrid multicopter configuration involving separate hover and cruise rotors and use fixed wings to produce a portion of the vehicle’s lift during cruise. The basic delivery mission is
assumed to involve take-off and climb to 400 feet, cruise at 50 miles per hour, and up to 60 seconds of hover and/or climb in the delivery area. The simulation allows for a 10 km/hr (kilometers per hour) headwind in each direction and leaves a 20-percent energy reserve upon returning to the depot.

For this design and mission, research by Jia Xu estimates fuel economy on the order of 460 MPGe. This allows the 20 percent of deliveries handled by drones to be conducted with the energy equivalent of 20.4 gallons of diesel. We subtracted this from the 46.8 gallons of diesel saved by the trucks. This results in a savings of the equivalent of 26.4 gallons of diesel for an overall net savings of about 5.7 percent for the 10-mile radius containing the bulk of the urban area when drones are used to cover 20 percent of the stops as compared with using trucks to make the same deliveries.

Note that the savings here, while modest in absolute terms, are quite robust. Even if the drone fleet achieved half of the estimated 460 MPGe in actual practice, the fleet would still require less energy (40.8 gallons equivalent) than would be saved by not using the trucks (46.8 gallons).
Chapter Three. Conclusions

In this analysis, we set out to get a sense of the difference in energy usage if 20 percent of delivery stops could be serviced by drones instead of trucks. We conducted the analysis by constructing a simple simulation model using real data for an actual city: Minneapolis, Minnesota. While the numbers and calculations in this preliminary study are rough, the analysis supports the idea that the energy requirements for truck and drone delivery for small packages are of the same order of magnitude and that drones may already be somewhat more energy-efficient for delivering small (5 lbs or less) packages within a 10-mile radius. Overall, we found that if 20 percent of stops involve delivery of 5 lbs or less of material, shifting the servicing of these stops to drones could save as much as 5.7 percent of the energy used to deliver packages within 10 miles of the center of Minneapolis. While practical considerations of noise abatement and airspace restriction might reduce this efficiency somewhat, rapid advances in battery technology and drone design can be expected to produce more than offsetting increases in efficiency, as related research by Jia Xu notes.

It should also be noted that the drone energy use would be entirely electric. Depending on sourcing of this power, it would be expected to have a much lower carbon footprint and to produce less local air pollution.

The savings found here come primarily from the fact that trucks are vastly heavier than drones. Although flying is a more energy-intensive form of locomotion—all things being equal—all things are not equal in this case. By using drones to deliver only the lightest packages, the deliverer is able to free the truck, with its greater weight and additional cargo, from the additional driving required to deliver that small package. By reducing the number of service areas required, this scheme also reduces the amount of “stem” driving required for trucks to reach their service areas from the depot and return.

This analysis indicates that drones may be an energy-saving way to deliver light packages, although they are unlikely to replace trucks for heavier items.


