What’s the Buzz?
The City-Scale Impacts of Drone Delivery

Andrew J. Lohn
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 (UPS), DHL, and Alibaba have been running high-profile experiments testing drone delivery systems, and the development of such systems reached a milestone when the first commercial drone delivery approved by the Federal Aviation Administration took place on July 17, 2015. In the future, drones could augment, or in some situations even replace, truck fleets and could have important implications for energy consumption, public safety, personal privacy, air pollution, city noise, air traffic management, road congestion, urban planning, and goods and service consumption patterns in urban areas.

To support developing issues 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 explore 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:

- Jia Xu’s research report on the design perspectives on delivery drones
- Kenneth Kuhn’s perspective on certification and traffic management of drones
- Therese Jones’s perspective on international drone regulation and drone delivery services
- Tim Gulden’s perspective using geographic information systems to compare truck versus delivery drone energy use
- Rebecca Balebako’s perspective on a research agenda for delivery UAVs and privacy
- Shira Efron’s perspective on delivery drones in urban and rural environments.

**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 protection and homeland security, transportation and energy policy, and environmental and natural resource policy.

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Summary

Drones are being pursued as a possible mechanism for large-scale delivery. Although the delivery companies involved must ensure that the approach they use is practical and economical, they are not as inclined to consider the external and indirect costs (what economists call externalities) that the population at large faces from the use of such drones. It is left to policymakers, drawing on inputs from industry and others, to understand what effects to anticipate and what options are available for ensuring the well-being of citizens without stifling innovation and business opportunities. The lack of precedent for large-scale delivery drones and the proprietary nature of both the aircraft designs and the business models increase the challenges that regulators and policymakers face in gaining that understanding, but simple mathematical models can help fill in the gaps. The models we created and present in this report provide a way to understand the scale of the problems that may arise and the relationships or trade-offs that exist. We use these models to help understand energy consumption, infrastructure requirements, aerial congestion, privacy, and noise for a range of hypothetical cities.

We derive an equation describing the energy consumed for a city based on parameters related to the city, the delivery vehicles, and the percentage of packages delivered by drone. The model includes the energy used for truck-based deliveries and that used for drone-based ones; it finds that increasing the percentage of packages delivered by drone can increase the energy consumed per package delivered substantially—by up to an order of magnitude in some cases. The reason for this is that for large cities, the drones have to repeatedly fly relatively long distances, whereas trucks can drive that distance once and then deliver many packages within a smaller region. However, in the short term, trucks will be primarily gas-powered and drones are more likely to be electric-powered, potentially using renewable sources; in addition, the energy per drone-delivered package can be significantly reduced by having many drone centers distributed throughout a city or region instead of using one centralized center.

Providing many distributed drone centers also decreases the number of drones required to service a city. We derive a queuing theory model to estimate the number of drones required to ensure a given level of service (the probability of having at least one drone available at all times). An increased number of drone centers decreases the time per flight, thus allowing for more deliveries with fewer drones. But that relationship breaks down for large numbers of drone centers; the size of the community serviced by an individual drone center decreases, and random fluctuations lead to more instances of outsized order volume.

1 This report is part of a larger series of products related to different facets of the delivery drone system and the likely impact of drone logistics on a city and the public. Although I am the sole author of this report, several people contributed to the research contained herein, so I often employ we when describing research conducted or steps taken.
Issues related to congestion, privacy, and noise also all benefit from an increased number of drone centers. Drones delivering packages will depart from, and return to, their drone center, which means that regions of a city near a delivery center should expect more drone activity overhead than those far from one. However, having more drone centers means that drones have to fly over fewer regions of a city to reach their destinations. So, for more parts of a city, having more drone centers and therefore shorter flights leads to fewer drones overhead, which can significantly improve concerns related to privacy and congestion.

The associated noise from aerial delivery vehicles may also be less than the range commonly experienced in cities, even relatively near the drone centers. Our simple models suggest that the noise levels fall off quickly with distance, such that even a drone as loud as a lawn mower would be barely audible at its traveling height (about 100 m). Additionally, the volume increases slowly as more drones are introduced, so there would need to be many drones directly overhead to surpass the noise volume of city traffic.

More research will be required as the business plans and vehicle designs become clear, but models such as those presented in this report can be used at this early stage to help policymakers understand the rough magnitude of the issues and the options available to them. By using models like these to understand energy consumption, infrastructure requirements, aerial congestion, privacy, and noise, policymakers (and interested parties in the private sector) can have an improved footing from which to address their primary concerns, and the benefits of drone delivery systems can be realized while minimizing the possible adverse effects.
Acknowledgments

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## Variables

\( \alpha \)  
rate of orders  

\( \gamma_{\text{eff}} \)  
vertical transfer efficiency  

\( \eta_{\text{drones}} \)  
energy consumed per kilometer for drone  

\( \eta_{\text{laden}} \)  
energy consumed per kilometer for drone with package  

\( \eta_{\text{truck}} \)  
energy consumed per kilometer for trucks  

\( \eta_{\text{unladen}} \)  
energy consumed per kilometer for drone without package  

\( \theta_{\text{max}} \)  
angle for calculating area of drone center \((\pi/6 \text{ radians})\)  

\( \mu \)  
power transfer efficiency  

\( \rho_{\text{air}} \)  
air density  

\( \rho_{b} \)  
specific power of battery  

\( \tau \)  
average duration of drone delivery trip  

\( A_{\text{city}} \)  
area of a city  

\( A_{z} \)  
area of a delivery zone  

\( C_{1} \)  
geometrical constant for truck deliveries  

\( C_{2} \)  
geometrical constant for truck deliveries  

\( C_{3} \)  
constant relating to aeronautical parameters  

\( C_{4} \)  
constant relating to aeronautical parameters  

\( d \)  
number of drones per drone center\(^1\)  

\( D \)  
number of drone centers  

\( d_{\text{max}} \)  
maximum distance drone must fly  

\( d_{z} \)  
expected distance traveled for truck in delivery zone  

\( e \)  
Euler’s number  

\( E \)  
energy consumed  

\( E_{\text{drones–horizontal}} \)  
energy consumed for horizontal component of drone trip  

\( E_{\text{drones–vertical}} \)  
energy consumed for vertical component of drone trip  

\( E_{\text{legs}} \)  
energy consumed to drive to delivery location or drone centers  

\( E_{\text{trucks}} \)  
energy consumed by trucks  

\( E_{\text{vertical}} \)  
energy consumed for vertical portions of drone flight  

\( g \)  
gravity  

\( h \)  
half the distance between drone centers in a hexagonal geometry  

\( h_{1} \)  
distance to drone  

\( h_{2} \)  
reference distance to drone  

\( h_{\text{cruise}} \)  
cruising altitude  

---

\(^1\) Except in Appendix A, where \( d \) means distance.
dummy variable used for iteration in summation

gеometrical constant for traveling salesman approximation

maximum horizontal distance from drone (for overhead or collision avoidance)

volume of sound

reference noise volume

noise volume for observer

airframe mass fraction

avionics mass

mass of battery

mass of drone without battery or package

avionics mass that is fixed

fraction of drone mass that is variable

design mass margin

mass of package

systems mass fraction

number of drones (for purposes of noise)

number of motors

average number of packages delivered per truck stop

average number of packages delivered per truck stop if no packages are delivered by drones

total number of packages delivered per day by truck

total number of packages to deliver per day

number of drones overhead

percentage of packages delivered by drone

computing and sensing power

probability of having to wait for a drone to become available

lift-to-drag ratio

distance from the nearest drone center

maximum radius of the area serviced by a drone center

length of rotor blades (radius)

number of stops

number of stops per delivery zone

amount of time over which packages are delivered

cruising velocity

vertical velocity

headwind-to-airspeed ratio

number of delivery zones
Chapter One. Introduction

Although commercial drones have now begun delivering commercial packages and research is starting to address delivery drone logistics, policymakers understand very little about the impact that the widespread adoption of delivery drones would have on cities around the world. There are a wide range of expected positive effects, including economic benefits, convenience, and delivery of time-critical goods and services to difficult-to-reach places. But there is also potential for negative effects related to aerial congestion, privacy, noise, energy consumption, and air pollution. Weighing these myriad costs and benefits has been difficult because robust data sources are unavailable, a large-scale drone delivery system has not yet been attempted anywhere in the world, and the detailed drone designs and business plans are proprietary information.

Despite these concerns, for the purpose of guiding regulation and for understanding how the rise of drone logistics will influence cities and their population, much can be understood without detailed data about the city, business plan, or drone design; this includes the relationships between key variables and an understanding of the scale of the expected impacts. Understanding the relationships would guide trade-offs to ensure that the ultimate solutions are acceptable to all stakeholders, and understanding the scale would allow policymakers to prioritize issues. Related guidance is being developed for short-range passenger aircraft, such as that outlined in Uber’s


white paper on its Uber Elevate service, but city-scale delivery drones provide different designs, use cases, and possible concerns. Because some of the regulatory and design decisions are being made at the outset of a new industry and can affect the industry over its entire lifetime, now is the time to focus on better understanding these concerns to make sure that drones take off on the right path.

Objectives and Approach

In this report, we explore the city-scale impacts of delivery drone operations on the following areas: energy consumption, infrastructure requirements, aerial congestion, privacy, and noise. The lack of precedent for large-scale delivery drones and the proprietary nature of both the aircraft designs and the business models increase the challenges that policymakers face in gaining that understanding, but simple mathematical models can help fill in the gaps. The models we created and present in this report provide a means to understand the scale of the problems that may arise and the relationships or trade-offs that exist. We use these models to understand the implications of delivery drones for a range of hypothetical cities. In particular, we derive an equation describing the energy consumed for a city based on parameters related to the city, the delivery vehicles, and the percentage of packages delivered by drone. The model includes the energy used for truck-based deliveries and that used for drone-based deliveries. We also derive a queuing theory model to estimate the number of drones required to ensure a given level of service (probability of having at least one drone available at all times). Additionally, we provide simple models of aerial congestion, observable range of the ground fleet, and noise produced at the ground level.

Using these mathematical models and an underlying literature review and expert discussions, we address the following questions:

- How much energy will drone deliveries consume compared with truck deliveries?
- How much infrastructure would be required, and how would infrastructure choices affect other outcomes?
- How much aerial congestion can be expected throughout the city?
- What are the privacy implications of delivery drones? In particular, how much of a city could delivery drones be used to monitor?
- How much additional noise would drones contribute?

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7 This report is part of a larger series of products related to different facets of the delivery drone system and the likely impact of drone logistics on a city and the public. Although I am the sole author of this report, several people contributed to the research contained herein, so I often employ we when describing research conducted or steps taken.
Organization of This Report

In the remainder of this report, we use the models to answer these questions. In Chapter Two we discuss our findings on energy consumption, and in Chapter Three, we discuss our findings on infrastructure and the size of the fleet. In Chapter Four, we discuss our findings for aerial congestion, privacy, and noise. Chapter Five provides some conclusions. The two appendixes provide more detail on the modeling used in this report.
Chapter Two. Total Energy Consumption

In this chapter, we focus on how we developed our model to estimate total energy consumption using drones and trucks for delivery. The total energy consumed for deliveries in a city is the sum of the energy consumed by both delivery trucks and delivery drones. We estimate each by calculating the distance traveled and then multiplying by the trucks’ or drones’ respective energy consumption, which is treated as constant (15 mi per gallon, or 6.5 km per liter) for trucks and calculated according to aircraft design and city parameters for drones, as outlined later. Doing so required modeling delivery routes, transport to delivery zones, and energy consumption. Finally, we used our estimates to compare total energy consumption for four hypothetical cities based on real cities.

Delivery Routes

For delivery routes, we assumed that trucks carry many packages (typically several hundred depending on population density) and the driver can choose the order of the deliveries to minimize the driving distance—a task that is referred to as the *traveling salesman problem*, which is illustrated in panel (a) of Figure 2.1. We assume that drones carry one package each and can depart from any distribution center in the city. In this report, the delivery centers are assumed to be distributed in a hexagonal formation, as shown in panel (b) of Figure 2.1; alternative geometries lead to only small deviations. The city assumed here is treated as having uniform population density and delivery request rates. These assumptions are sufficient for identifying general trends and the scale of possible concerns or policy actions. Fine-tuned results for specific cities may require more-specific data for that city.

*Figure 2.1. Delivery Route Assumptions for Trucks (a) and Drones (b)*
In addition to carrying many packages, a truck is able to deliver more than one package per stop, the number of which is assumed to be Poisson-distributed with a mean that is treated as an input to the model and is expected to vary based on population density.

With these assumptions, the energy consumed ($E$) for deliveries in the city can be calculated according to Equation 2.1, using energy efficiencies and the distances derived in Appendix A. The city is represented by its total area ($A_{\text{city}}$), total number of packages to deliver per day ($N_o$), average number of packages per stop (trucks only) ($n_o$), percentage of packages delivered by drone ($p$), and the number of drone centers ($D$). The parameters contained in the vertical energy equation are summarized later (see Table 2.1).

$$E = E_{\text{trucks}} + E_{\text{drones-horizontal}} + E_{\text{drones-vertical}}$$  \hspace{1cm} \text{Eq. 2.1}

$$E_{\text{trucks}} \approx 0.765 \sqrt{\frac{N_o A_{\text{city}}}{n_o} \left[ 1 - \sum_{i=1}^{\infty} p^i \frac{n_o^i e^{-n_o}}{i!} \right]} \eta_{\text{truck}}$$  \hspace{1cm} \text{Eq. 2.1a}

$$E_{\text{drones-horizontal}} \approx 0.377 N_o p \sqrt{\frac{A_{\text{city}}}{D}} \left( \eta_{\text{laden}} + \eta_{\text{unladen}} \right)$$  \hspace{1cm} \text{Eq. 2.1b}

$$E_{\text{drones-vertical}} = N_o p \left[ \left( \frac{(m_p + m_d + m_b) g}{2 \rho_{\text{air}} n_{\text{motors}}^3 r_{\text{rotor}}^3} \right)^{3/2} + \left( \frac{(m_d + m_b) g}{v_{\text{cruise}} \gamma_{\text{eff}}} \right)^{3/2} \right] \sqrt{\frac{h_{\text{cruise}}}{v_{\text{vertical}} \gamma_{\text{eff}}}} + N_o p (m_p + 2m_d + 2m_b) g h_{\text{cruise}}$$  \hspace{1cm} \text{Eq. 2.1c}

The first term is the truck energy, the second is drone energy for horizontal flight, and the third is the energy (often negligible) needed for drones to get to their traveling height.\(^1\) The constants 0.765 and 0.377 are geometrical factors. The first is an empirical constant used to estimate the solution to the traveling salesman problem for a given number of stops in a given area based on an approximation that is most valid for 15 or more stops.\(^2\) (Trucks usually make about 100 stops.\(^3\)) The second term relates to the layout of the drone centers; the number shown here was calculated for a hexagonal arrangement like the one shown in Figure 2.1.

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Transport to Delivery Zones

Energy calculations should also consider the trips required for the trucks to reach their delivery zones from the main warehouse and the trips required for the drone centers to be restocked (Equation 2.2). These can be included by estimating the average distance to points in the city and then multiplying by the number of locations traveled to. For simplicity, we treat the main warehouse as located at the center of a circular city. Other points and geometries could be arbitrarily chosen, but doing so leads to relatively small differences in outcomes. This approach is more accurate for trucks than it is for drones. That is because when a delivery truck leaves the warehouse for deliveries, it needs to make the journey to its delivery region only once; however, a single truck leaving the warehouse may be able to restock several drone centers in one trip, or several trucks could be required to restock a single center. Detailed analysis would require knowing the volume of drone-delivered packages and the volume that can be carried by a truck. Our set of assumptions err on the conservative side relative to most of our results, and alternative assumptions make small changes that do not alter our main conclusions. The assumptions become highly inaccurate only when the number of drone centers is so large that it makes little practical sense to offer a delivery service by drone at all.

\[
E_{\text{legs}} = \eta_{\text{truck}} \left( C_1 \frac{N_o \sqrt{A_{\text{city}}}}{n_o} \left[ 1 - \sum_{i=1}^{\infty} p^i \frac{n_o}{i!} e^{-n_o} \right] + C_2 \sqrt{A_{\text{city}}D} \right) \tag{Eq. 2.2}
\]

\[
C_1 = \frac{2}{3 \sqrt{\pi} S_Z} \tag{Eq. 2.2a}
\]

\[
C_2 = \frac{2}{3 \sqrt{\pi}} \tag{Eq. 2.2b}
\]

The constants \(C_1\) and \(C_2\) are derived for the average distance to the points covering a circular area. The average distance is multiplied by the number of truck delivery zones required in the first term and by the number of drone centers in the second term. \(C_1\) requires an additional variable, \(S_Z\), the number of stops made per delivery zone. As noted earlier, this number is typically around 100 and can be estimated based on the length of a workday, the average time per stop, and the average driving speed.
Energy Efficiency

The total energy also depends on the energy efficiency ($\eta_{drones}$) of the drones, which is determined by aircraft design and city parameters and shown in Equation 2.3. Our estimates follow the approach taken in D’Andrea (2014) while allowing the battery size to vary to accommodate the required range and weight.4

$$\eta_{drones} = \frac{C_3}{1 - d_{\text{max}}/C_4}$$  \hspace{1cm} \text{Eq. 2.3}

$$C_3 = \frac{1}{(1 - \nu)} \left[ \frac{m_p + m_d}{\mu r} + \frac{p_{\text{avionics}}}{w} \right]$$  \hspace{1cm} \text{Eq. 2.3a}

$$C_4 = \frac{\rho_b (1 - \nu) \mu r_{\text{ltd}}}{2}$$  \hspace{1cm} \text{Eq. 2.3b}

$$d_{\text{max}} = \frac{2A_{\text{city}}}{\sqrt{3\sqrt{3}D}}$$  \hspace{1cm} \text{Eq. 2.3c}

Here, $d_{\text{max}}$ is the largest distance a drone can expect to fly within its zone and is calculated directly from the geometry of the drone delivery zones. It is therefore proportional to the square root of the city area divided by the number of drone centers. The other variables are related to aircraft design, consistent with those expected to be used in Amazon’s delivery drone and described in Table 2.1.5

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Table 2.1. Drone Design Parameters Used to Calculate Energy Efficiency

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$w$</td>
<td>Headwind-to-airspeed ratio</td>
<td>3/8</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Power transfer efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>$r_{ldd}$</td>
<td>Lift-to-drag ratio</td>
<td>3</td>
</tr>
<tr>
<td>$p_{avionics}$</td>
<td>Computing and sensing power</td>
<td>0.1 kW</td>
</tr>
<tr>
<td>$v$</td>
<td>Cruising velocity</td>
<td>80 km/h</td>
</tr>
<tr>
<td>$\rho_b$</td>
<td>Specific power of battery</td>
<td>0.35 kW/kg</td>
</tr>
<tr>
<td>$n_{motors}$</td>
<td>Number of motors</td>
<td>4</td>
</tr>
<tr>
<td>$r_{rotor}$</td>
<td>Length of rotor blades (radius)</td>
<td>0.15 m</td>
</tr>
<tr>
<td>$v_{vertical}$</td>
<td>Vertical velocity</td>
<td>10 km/h</td>
</tr>
<tr>
<td>$\gamma_{eff}$</td>
<td>Vertical transfer efficiency</td>
<td>0.5</td>
</tr>
<tr>
<td>$\rho_{air}$</td>
<td>Air density</td>
<td>1.225 kg/m$^3$</td>
</tr>
<tr>
<td>$g$</td>
<td>Gravity</td>
<td>9.8 m/s</td>
</tr>
<tr>
<td>$h_{cruise}$</td>
<td>Cruising altitude</td>
<td>100 m</td>
</tr>
<tr>
<td>$m_{avionics}$</td>
<td>Avionics mass</td>
<td>0.4</td>
</tr>
<tr>
<td>$m_{airframe}$</td>
<td>Airframe mass fraction</td>
<td>30%</td>
</tr>
<tr>
<td>$m_{systems}$</td>
<td>Systems mass fraction</td>
<td>15%</td>
</tr>
<tr>
<td>$m_{margin}$</td>
<td>Design mass margin</td>
<td>10%</td>
</tr>
<tr>
<td>$m_p$</td>
<td>Mass of package</td>
<td>2 kg laden, 0 kg unladen</td>
</tr>
</tbody>
</table>

It is outside the scope of this report to conduct a detailed exploration of the aircraft design, but it is important to consider how aircraft design, city design, and logistics affect each other. With regard to drone mass, except where specified otherwise, this report follows the approach taken by Jia Xu in forthcoming complementary research in this series, whereby most of the drone mass is specified as percentages of total mass, allowing for smaller designs for smaller payloads and energy requirements. Figure 2.2 shows the energy consumption per kilometer kilogram flown for laden (blue) and unladen (orange) drones, considering only the cruising energy according to Equation 2.2. This does not include the vertical takeoff and landing energies, which total an additional 0.12 kilowatt-hours (kWh) for a 2-kg package and a 2-kg battery.
Figure 2.2. Energy Consumption per Kilometer Kilogram for Laden (Blue) and Unladen (Orange) Drones

The package mass, number of drone centers, area of the city, and cruising velocity (the four sets of curves starting at the top of the figure) were held at 2 kg, one drone center, 1,500 km$^2$, and 80 km/h, respectively, when not varied in Figure 2.2. Although energy increases substantially for heavier packages, the curves in Figure 2.2 show that the per-kilogram efficiency increases initially and flattens out relatively quickly as more battery and drone weight are needed to support the payload. For similar reasons, the efficiency decreases substantially in panel (c), as area of the city grows. More battery weight is needed to traverse longer distances. Reducing distances is a way to maintain high efficiencies; thus, there is a significant efficiency improvement for increasing the number of drone centers, but the marginal payoff decreases as additional drone centers are included. For comparison, the 15 mi-per-gallon trucks consume the equivalent of about 1.6 kWh/km, so if one truck can carry 250 packages weighing 2 kg, the comparable efficiency would be 0.0032 kWh/(km kg), or about an order of magnitude better. If more or heavier packages are delivered by truck, then efficiency improves further. Importantly, these results are only the vehicle energy efficiency, which is just a component of the total energy consumption, which depends on the number of flights, the lengths traveled, and the consumption of delivery trucks as well. Next, we turn to total energy consumption.
Total Energy Consumption

Incorporating Equation 2.2 and Equation 2.3 into Equation 2.1 gives the total energy consumed by a city for deliveries, as shown in Equation 2.4.

\[
E = \left( c_1 \sqrt{\frac{N_o A_{city}}{n_o}} \left[ 1 - \sum_{i=1}^{\infty} \frac{p_i n_o^i e^{-n_o}}{i!} \right] + c_3 \frac{N_o \sqrt{A_{city}}}{n_o} \left[ 1 - \sum_{i=1}^{\infty} \frac{p_i n_o^i e^{-n_o}}{i!} \right] + c_4 \sqrt{A_{city} D} \right) \eta_{Truck} + c_2 N_o p \sqrt{A_{city} D} \left( \eta_{Laden} + \eta_{Unladen} \right) + E_{vertical}
\]

Eq. 2.4

Although this equation may appear complicated, several simple approximate relationships can be seen. Ignoring the vertical component \( E_{vertical} \), the energy consumed increases with the square root of the area of the city for both drones and trucks. Energy for flying the drones increases linearly with number of packages and for the percentage of packages delivered by drone, and it decreases with the square root of the number of drone centers. Truck energy increases somewhere between square root and linearly with number of packages depending on the specifics of the city. These relationships can be seen more exactly by computing the results for several hypothetical cities, which we do in the next section, and Appendix B provides a simple sensitivity analysis showing the variation in energy per package for plus and minus 10-percent variation in each of the parameters.

Comparing Cities

We also examined the aforementioned framework under urban scenarios modeled after real cities. We used four hypothetical cities for modeling energy consumption, modeled roughly (uniform population density) after Los Angeles, California; Tokyo, Japan; Kigali, Rwanda; and Minneapolis, Minnesota. Figure 2.3 shows the energy consumption per package delivered for the four hypothetical cities. The parameters used for each city are shown in Table 2.2.
Figure 2.3. Total Energy Consumed per Package Delivered, by Hypothetical City for One Drone Center

(a) Variable Drone Mass

(b) Fixed Drone Mass – 25kg

Table 2.2. Parameters Used to Compare Cities’ Energy Consumption

<table>
<thead>
<tr>
<th>City</th>
<th>Area of City (km²)</th>
<th>Population Density (km⁻²)</th>
<th>Packages per Person per Day</th>
<th>Packages per City per Day</th>
<th>Packages per Stop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Los Angeles–sized</td>
<td>1,500</td>
<td>4,000</td>
<td>0.04</td>
<td>250,000</td>
<td>3</td>
</tr>
<tr>
<td>Tokyo–sized</td>
<td>2,500</td>
<td>7,000</td>
<td>0.04</td>
<td>700,000</td>
<td>10</td>
</tr>
<tr>
<td>Kigali–sized</td>
<td>750</td>
<td>1,500</td>
<td>0.04</td>
<td>45,000</td>
<td>1</td>
</tr>
<tr>
<td>Minneapolis–sized</td>
<td>150</td>
<td>3,000</td>
<td>0.04</td>
<td>18,000</td>
<td>2</td>
</tr>
</tbody>
</table>
The number of packages per day is estimated from the 18.3 million deliveries per day reported by the United Parcel Service (UPS),\(^6\) about half of which are business-to-customer as opposed to business-to-business\(^7\) and may therefore be more likely to remain serviced by truck because of larger volumes. The U.S. population is about 320 million people and 75 percent of UPS deliveries are in the United States,\(^8\) so we estimate that about 0.02 packages are delivered per person per day. Because UPS has approximately 54 percent of the market share,\(^9\) the total number of packages to be delivered is about 0.04 per person per day (as shown in Table 2.2). For the computations, the three main delivery services are treated separately and then added together; treating them as one independent service would make trucks seem more efficient than they are. So, the market has been divided into segments—UPS: 54 percent; FedEx: 30 percent; and the U.S. Postal Service (USPS): 16 percent.

The energy consumed for package delivery grows rapidly as the fraction of packages delivered by drones increases. In Figure 2.3, the y-axis shows the energy consumed per package as the fraction of packages delivered by drone increases on the x-axis. Panel (a) of the figure shows the energy consumption for the variable mass described in Table 2.1. Heavier drones may be used, though, so panel (b) shows the energy consumption that would be expected if the drone, package, and battery were to have a combined mass of 25 kg.

Figure 2.4 shows the energy per package as well but expressed as a multiple of the energy consumed if all packages are delivered by trucks. (The trucks-only energy is the normalization constant with values of 0.24, 0.16, 0.49, and 0.24 kWh per package, respectively, for the Los Angeles–sized, Tokyo-sized, Kigali-sized, and Minneapolis-sized cities.) For a single drone center, the increase in energy per package ranges from a little more than 10 percent for the Kigali-sized city to a factor of about ten for the Tokyo-sized city. The dramatic increase in energy consumption as compared with trucks-only deliveries is caused by the long distances the drone must fly and the relative efficiency of trucks that are able to carry multiple packages and optimize their routes. However, drone delivery becomes much less energy intensive as the number of drone centers is increased, and, for small cities, the energy used can even be less than that for trucks. Combined with the significantly reduced delivery time lines, it seems that a strong case can be made for drone delivery in at least some environments.

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\(^8\) CSI Market, “United Parcel Service Inc (UPS) Divisions, Quarterly Segment Results,” undated.

The same quantities are shown in Figure 2.5, where the number of drone centers for each city ranges from five to 20 instead of from one to five as in Figure 2.4. In Figure 2.5, the drone energy differential as a multiple of the trucks-only energy varies from about 30-percent savings for the Kigali-sized and Minneapolis-sized cities to a factor of almost three for the Tokyo-sized city. That can still be a large energy-consumption cost for the additional speed and convenience of drone delivery, but increasing the number of drone centers makes the increase in energy much more manageable.
Figure 2.5. Total Energy Consumed per Package Delivered, by Hypothetical City and Number of Drone Centers (5–20)
Aside from providing energetic benefits (such as those discussed in the previous chapter), infrastructure decisions, such as number of drone centers, must consider such issues as the required size of the drone fleet and the degree of encroachment into populated or otherwise occupied spaces. This chapter discusses these infrastructure decisions.

The average distance separating centers can be estimated directly from the area of the city and the number of centers, again assuming the honeycomb pattern shown in panel (b) of Figure 2.1. But the number of drones required per center is a standard queuing theory problem. Therefore, to estimate the size of the fleet required to service the city, we use the Erlang C formula (Equation 3.1), which calculates the probability that all drones will be occupied when an order comes in.

\[
P_q = \frac{(\alpha \tau)^d d}{d! (d - \alpha \tau)} \sum_{i=0}^{d-1} \frac{(\alpha \tau)^i}{i!} + \frac{(\alpha \tau)^d d}{d! (d - \alpha \tau)}
\]

\[
\alpha \tau = \frac{N_o p C_2 A_{city}^{1/2}}{TD^2 v}
\]

\[
\alpha \tau = \frac{2N_o p}{TD} \left[ \frac{C_2 A_{city}^{1/2}}{D^{1/2} v} + \frac{h_{cruise}}{v_{vertical}} \right]
\]

In Equation 3.1, \(P_q\) is the probability of an order having to wait for a drone to become available, \(\alpha\) is the rate of orders, \(\tau\) is the average duration of a trip, \(T\) is the amount of time over which packages are delivered, and \(d\) is the number of drones per center.

The number of drones required per center \((d)\) is closely tied to the traffic \((\alpha \tau)\), which, ignoring the time for vertical takeoff, is inversely proportional to the number of delivery centers to the 3/2 power. The traffic for the entire city is simply the traffic per center multiplied by the number of centers \((\alpha \tau D)\), which is inversely proportional to the square root of the number of centers. The result is that increasing the number of centers should decrease the total number of drones needed for the city, but that intuitive description ignores the queuing problem, which requires solving Equation 3.1, as illustrated in Figure 3.1.
Figure 3.1, which varies the number of drone centers from one to 100, uses a Los Angeles–sized city as the example, with 86 percent of packages delivered by drone ($p = 0.86$) and with all packages delivered at a constant rate over a 16-hour period ($T = 16$). As the number of drone centers increases, there is a substantial reduction in the number of drones required for the city, but only up to a point. Further increases in the number of centers sacrifices the ability to accommodate fluctuations in demand; because any additional drone provided to every center increases the total number for the city substantially, the total number of drones required begins to increase. Note also that this analysis presumes that any of the drones can be deployed for any delivery within the center’s region. If several different companies compete and do not share resources, then Equation 3.1 should be solved for each company and a larger total number of drones would be expected.

We do not have data for the cost of drone centers or the cost of the drones themselves, but these results suggest that capital costs of additional drone centers may be offset, at least partially, by the reduced number of drones required. Those savings are in addition to the substantial energy and emission savings from having additional drone centers.

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Chapter Four. Aerial Congestion, Privacy, and Noise

Increasing the number of drone centers makes it difficult to place them only in low-traffic and nonresidential areas, which may lead to concern about aerial congestion, privacy, and noise.

Aerial Congestion and Privacy

The number of drones flying overhead depends on distance from a drone delivery center. The number of flights that go at least as far as a given radius from the nearest center is the total number of flights minus those that are delivered within that radius. And the amount of time a drone spends at that radius decreases if the drones travel faster. Combining these two concepts, the number of drones that can be expected overhead is expressed in Equation 4.1.

\[
N_{\text{overhead}} = \frac{2N_o p}{TD} \left(1 - \frac{r^2}{R^2}\right) \frac{l^2}{2rv}
\]

Eq. 4.1

In Equation 4.1, \(r\) is the distance from the nearest drone center, \(R\) is the maximum radius of the area serviced by the drone center, and \(l\) is the maximum horizontal distance from the drone at which the drone may be a concern. For congestion, \(l\) may be the radius for which sense-and-avoid is required, and for privacy, \(l\) may be the field of view of common cameras. Importantly, the expected number of drones overhead decreases as the number of drone centers increases, because the number of drones being launched per center decreases; however, the expected number of drones overhead is complicated by the increase in the number of locations from which they are being launched. A more useful metric is the fraction of the city that has more than a specified expected number of drones overhead at any given time. That metric is shown in Figure 4.1, where the region being considered is 200 m—the approximate field of view of a wide-angle camera from the 100-m altitude specified by the Federal Aviation Administration.\(^1\) This 200-m range will be used to assess the potential impact to privacy by deriving the expected number of drones that would be within monitoring range of a person at any given time depending on how far they are from a drone center.

---

Figure 4.1 shows the results for a Los Angeles–sized city and uses the same parameters as were used for determining the number of drones required in Figure 3.1. The number of drone centers is again varied from one to 100. As shown by the dotted black lines, with only one drone center, almost a quarter of the city should expect to have a drone within camera range or within approximately a city block half of the time. That number drops dramatically with a larger number of drone centers. It may seem counterintuitive that placing drone centers near populated areas can reduce the likelihood of that population encountering drones, but it is simply a byproduct of eliminating the need for drones to fly over one region to get to other regions of the city. Thus, managing the number of drone centers can dramatically reduce aerial congestion, as well as the privacy concerns and the noise that arise from having many drones overhead.

**Noise**

Estimating the amount of noise to be expected from a city-scale drone delivery system is challenging because data do not exist for the noise generation or acoustic profile of these vehicles and because they are still likely to undergo substantial redesigns. However, some simple approximations can be used to gain key insights about the scale of the issue and the important relationships or trade-offs available. Asserting a noise level near the drone and using the inverse square law shown in Equation 4.2, we can estimate the sound levels at the ground.
$$L_2 = L_1 - \left| 10 \log \left( \frac{h_1}{h_2} \right)^2 \right|$$ \hspace{1cm} \text{Eq. 4.2}

Consistent with current regulations restricting flying heights to 400 ft to avoid conventional air traffic,\(^2\) we use 100 m as our distance from the drone to the ground \((h_1)\). Treating the drone volume as 90 decibels (dB) \((L_1)\) at 1 m \((h_2)\), which is comparable to a power mower or garbage disposal, we expect a sound level on the ground of about 50 dB, which is comparable to the background noise levels in urban environments.

If there are many drones overhead, the volume will increase, but it does not increase rapidly. For incoherent noise sources like drones, the change in volume is logarithmic with the number of drones \((n_d)\), as shown in Equation 4.3.

$$\Delta L = 10 \log (n_d)$$ \hspace{1cm} \text{Eq. 4.3}

To get to a volume comparable to city traffic (70 dB), one would need 100 drones directly overhead. The increase in noise from no drones to one drone or from one drone to several drones may be noticeable, but the subsequent addition of drones does less to increase noise exposure, as shown in Figure 4.2. Of course, the degree of annoyance will depend on the combination of the volume of noise and the frequency and number of flights overhead, as well as many other factors, such as personal perception. In some areas, the noise levels may be sufficiently low as to not contribute to annoyance, and in others, they could be high enough to be widely viewed as unacceptable. Figure 4.2 helps illustrate such ranges.

---

\(^2\) Federal Aviation Administration, 2016.
Figure 4.2 shows that being near even a small drone center could cause a noticeable increase in noise, although even the ten drones from the 30-m level is still within common volumes for urban environments. Away from the center, if noise is a persistent issue, it may be possible to alleviate the issue significantly by altering the flying height. Relatively small changes in height can have a larger effect than reducing the number of drones generating the noise. Alternatively, there are efforts under way to design quieter vehicles.3

---

Besides the potential for designing quieter drones, there are many ways for revolutionary business models or novel vehicle designs to alter the results of this analysis in unexpected ways. For example, this report does not consider drone-truck hybrids, in which the truck acts as a mobile drone center. Further, we have not addressed any changes in demand that might occur because of increased convenience, business plans that service only segments of a city, or shifts to include very heavy packages or passengers, and we have also not addressed the potential for drones that carry multiple packages.

Although there is still much work to be done and any policies, regulations, or business plans will have to deal with a high degree of uncertainty, we have demonstrated several important relationships that should be expected if drone delivery takes off. In some cases, such as energy consumption, the change compared with the status quo can be up to an order of magnitude. That increased energy consumption can be dramatically reduced by requiring the use of many drone centers. In fact, requiring many drone centers has the additional benefits of reducing the size of the fleet, aerial congestion, and the privacy and noise concerns that overhead drones create. Building many drone centers in a city could be challenging, given that neighborhoods may oppose new construction, but doing so may provide those same neighborhoods with significant benefit.
Appendix A. Derivation of the Energy Equations

This appendix shows the derivation of components of the energy consumption equations.

Distance Traveled by Trucks

The trucks are divided into $Z$ delivery zones, in which each truck makes $S_Z$ stops in that zone, delivering, on average, $n$ packages per stop for a total of $N$ packages per day.

\[
Z = \frac{N}{S_Z n} \quad \text{Eq. A.1a}
\]

\[
A_Z = \frac{A_{city}}{Z} \quad \text{Eq. A.1b}
\]

For the traveling salesman problem, the expected distance traveled with $S_Z$ stops uniformly distributed over $A_Z$ area is as follows:\(^1\)

\[
d_Z = k_{TSP} \sqrt{S_Z} \sqrt{A_Z} \quad \text{Eq. A.2}
\]

The total distance traveled for all zones is therefore

\[
d_{total} = d_Z Z = k_{TSP} \sqrt{S_Z} \sqrt{A_Z} Z \quad \text{Eq. A.3}
\]

Substituting Equations A.1 and A.2 into Equation A.3 gives us

\[
d_{total} = k_{TSP} \sqrt{\frac{A_{city} N}{n}} \quad \text{Eq. A.4}
\]

---

\(^1\) For Equation A.1, see Stein, 1978. For Equation A.2, see Eilon, Watson-Gandy, and Christofides, 1971. In this appendix, $d$ refers to distance, not drones per drone center.
Both \( N \) (total number of packages delivered by truck) and \( n \) (average number delivered per truck stop) depend on the percentage of packages delivered by drone. The total number delivered by truck is \( N = N_o (1 - p) \), which comes from simply subtracting the number of packages delivered by drone. The average number of packages delivered per stop is more complicated. It can be found by dividing the total number of truck-delivered packages by the total number of stops made. Assuming that the number of packages per stop is Poisson-distributed and that packages are removed from those potential stops to be delivered by drone instead, the probability that a stop has no packages left for truck delivery is

\[
S_{total} = S_o \left[1 - \sum_{i=1}^{\infty} p^i \frac{n_o^i e^{-n_o}}{i!}\right] \quad \text{Eq. A.5}
\]

The intuition behind Equation A.5 is that all the packages destined for a stop must be transferred to drones for that stop to be removed. That probability is \( p^i \), where \( p \) is the probability of drone delivery and \( i \) is the number of packages destined for that stop. Multiplying that by the probability of having \( i \) packages per stop (i.e., \( \frac{n_o^i e^{-n_o}}{i!} \)) and integrating over all possible \( i \) gives the sum on the right-hand side of the equation. Subtracting the sum from 1 gives the percentage of stops remaining to be serviced by truck.

The average number of packages per stop can then be calculated as follows, remembering that \( S_o = \frac{N_o}{n_o} \):

\[
n = \frac{N}{S} = \frac{N_o (1 - p)}{n_o \left[1 - \sum_{i=1}^{\infty} p^i \frac{n_o^i e^{-n_o}}{i!}\right]} \quad \text{Eq. A.6a}
\]

\[
n = \frac{n_o (1 - p)}{\left[1 - \sum_{i=1}^{\infty} p^i \frac{n_o^i e^{-n_o}}{i!}\right]} \quad \text{Eq. A.6b}
\]

Substituting Equation A.6 into A.5 gives

\[
d_{total} = k_{TSP} \sqrt{\frac{N_o A_{city}}{n_o} \left[1 - \sum_{i=1}^{\infty} p^i \frac{n_o^i e^{-n_o}}{i!}\right]} \quad \text{Eq. A.7}
\]
Distance Traveled by Drones

Drones can deliver to a circular area surrounding a drone center, where the radius is determined by the range of the drone. The drone centers can be efficiently packed in a hexagon, where the edges of the hexagon are equidistant from two neighboring delivery centers. It is assumed that the drones do not cross that boundary, because locations across that boundary could be more efficiently serviced by a drone from the neighboring center. The geometry is illustrated in panel (a) of Figure A.1.

The average distance traveled by a drone is calculated by integrating the length of a trip (one-way distance) over the area of the hexagon and normalizing, as follows:

\[ d_{avg} = \frac{\iint \sqrt{x^2 + y^2} \, dA}{\iint dA} \]  
\( \text{Eq. A.8} \)

It is sufficient to integrate over the triangle corresponding to one-twelfth of the hexagon, as illustrated in panel (b) of Figure A.1, and then multiplying by 12.

\[ d_{avg} = \frac{\int_{y=0}^{y=h} \int_{x=0}^{x=\tan(\theta_{max})} \sqrt{x^2 + y^2} \, dx \, dy}{\frac{1}{2} (h \tan(\theta_{max}) h)} \]  
\( \text{Eq. A.9} \)

Figure A.1. Packing Drone Centers into a City Leads to Hexagonal Delivery Zones (a), the Area of Which Is Composed of 12 Triangles (b)
The inner integral can be solved by trigonometric substitution; then, the outer integral can be solved directly by the power law, resulting in Equation A.10:

\[ d_{avg} = \int_{y=0}^{y=h} \frac{2y^2/3 + \ln(\sqrt{3})}{2} dy = \frac{2}{3} + \ln(\sqrt{3}) \frac{h}{\sqrt{3}} \]

Eq. A.10

In that equation, \( h \) is the distance from the center of the hexagon to the edge of the hexagon, or half of the distance between neighboring drone centers. That can be calculated knowing the area of the city and number of drone centers.

\[ \frac{12h^2}{2\sqrt{3}} = \frac{A_{city}}{D} \]

Eq. A.11a

\[ h = \sqrt{\frac{2\sqrt{3}A_{city}}{12D}} \]

Eq. A.11b

Incorporating \( h \) into \( d_{avg} \) gives a one-way distance of

\[ d_{avg} = \frac{2}{3} + \ln(\sqrt{3}) \sqrt{\frac{2\sqrt{3}A_{city}}{12D}} \]

Eq. A.12
Appendix B. Sensitivity of Energy to Variation in Parameters

To illustrate which input parameters the energy model is more or less sensitive to, this appendix shows the energy per package delivered in kWh for slight variation in the parameters. The baseline case about which the parameters are varied is a Los Angeles–sized city with one drone center and 86 percent of packages delivered by drone. Each parameter is varied individually from the base case by plus and minus 10 percent.

### Table B.1. Drone Design Parameters Used to Calculate Energy Efficiency

<table>
<thead>
<tr>
<th>Symbol Used</th>
<th>Description</th>
<th>−10% (kWh)</th>
<th>Baseline (kWh)</th>
<th>+10% (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( p )</td>
<td>Percentage of packages delivered by drone</td>
<td>0.8623</td>
<td>0.9014</td>
<td>0.9447</td>
</tr>
<tr>
<td>( A_{city} )</td>
<td>Area of the city</td>
<td>0.8327</td>
<td>0.9104</td>
<td>0.9906</td>
</tr>
<tr>
<td>( N_o )</td>
<td>Total number of packages to deliver per day</td>
<td>0.9148</td>
<td>0.9104</td>
<td>0.9066</td>
</tr>
<tr>
<td>( n_o )</td>
<td>Average number of packages per truck stop</td>
<td>0.9171</td>
<td>0.9104</td>
<td>0.9055</td>
</tr>
<tr>
<td>( S_2 )</td>
<td>Number of truck stops per delivery zone</td>
<td>0.9152</td>
<td>0.9104</td>
<td>0.9065</td>
</tr>
<tr>
<td>( \eta_{truck} )</td>
<td>Truck energy efficiency</td>
<td>0.9242</td>
<td>0.9104</td>
<td>0.8992</td>
</tr>
<tr>
<td>( w )</td>
<td>Headwind-to-airspeed ratio</td>
<td>0.8321</td>
<td>0.9104</td>
<td>1.0086</td>
</tr>
<tr>
<td>( \mu )</td>
<td>Power transfer efficiency</td>
<td>1.0742</td>
<td>0.9104</td>
<td>0.7979</td>
</tr>
<tr>
<td>( \eta_{td} )</td>
<td>Lift-to-drag ratio</td>
<td>1.0742</td>
<td>0.9104</td>
<td>0.7979</td>
</tr>
<tr>
<td>( p_{avionics} )</td>
<td>Computing and sensing power</td>
<td>0.8985</td>
<td>0.9104</td>
<td>0.9224</td>
</tr>
<tr>
<td>( v )</td>
<td>Cruising velocity</td>
<td>0.9237</td>
<td>0.9104</td>
<td>0.8996</td>
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<tr>
<td>( \rho_b )</td>
<td>Specific power of battery</td>
<td>0.9954</td>
<td>0.9104</td>
<td>0.8524</td>
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<tr>
<td>( n_{motors} )</td>
<td>Number of motors</td>
<td>0.9117</td>
<td>0.9104</td>
<td>0.9094</td>
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<tr>
<td>( r_{rotor} )</td>
<td>Length of rotor blades (radius)</td>
<td>0.9130</td>
<td>0.9104</td>
<td>0.9083</td>
</tr>
<tr>
<td>( \psi_{vertical} )</td>
<td>Vertical velocity</td>
<td>0.9130</td>
<td>0.9104</td>
<td>0.9083</td>
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<tr>
<td>( \gamma_{eff} )</td>
<td>Vertical transfer efficiency</td>
<td>0.9130</td>
<td>0.9104</td>
<td>0.9083</td>
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<tr>
<td>( \rho_{air} )</td>
<td>Air density</td>
<td>0.9117</td>
<td>0.9104</td>
<td>0.9094</td>
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<tr>
<td>( h_{cruise} )</td>
<td>Cruising altitude</td>
<td>0.9081</td>
<td>0.9104</td>
<td>0.9127</td>
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<tr>
<td>( m_{fixed} )</td>
<td>Avionics mass that is fixed</td>
<td>0.8257</td>
<td>0.9104</td>
<td>0.9953</td>
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<td>( m_{variable} )</td>
<td>Fraction of drone mass that is variable</td>
<td>0.8816</td>
<td>0.9104</td>
<td>0.9827</td>
</tr>
<tr>
<td>( m_p )</td>
<td>Mass of package</td>
<td>0.9274</td>
<td>0.9104</td>
<td>0.8935</td>
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