# Strategic Design of Drone Delivery Systems

VIII International Workshop on Locational Analysis and Related Problems

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James F. Campbell, Don Sweeney,
Juan Zhang, Deng Pan
*University of Missouri-St. Louis*
*St. Louis, MO*

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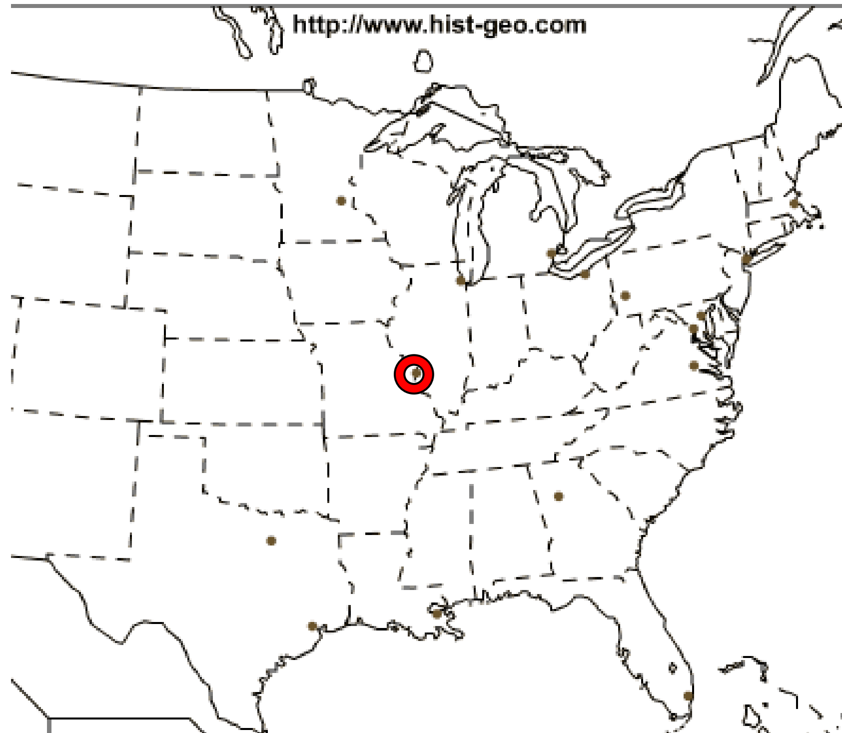
REDLOCA
RED DE LOCALIZACIÓN Y PROBLEMAS AFINES

# UMSL and St. Louis

- St. Louis:
  - 2.8 million people on the Mississippi River
  - Distribution center
  - Major businesses: Boeing, Anheuser-Busch (AB InBev), Monsanto
  - University of Missouri-St. Louis

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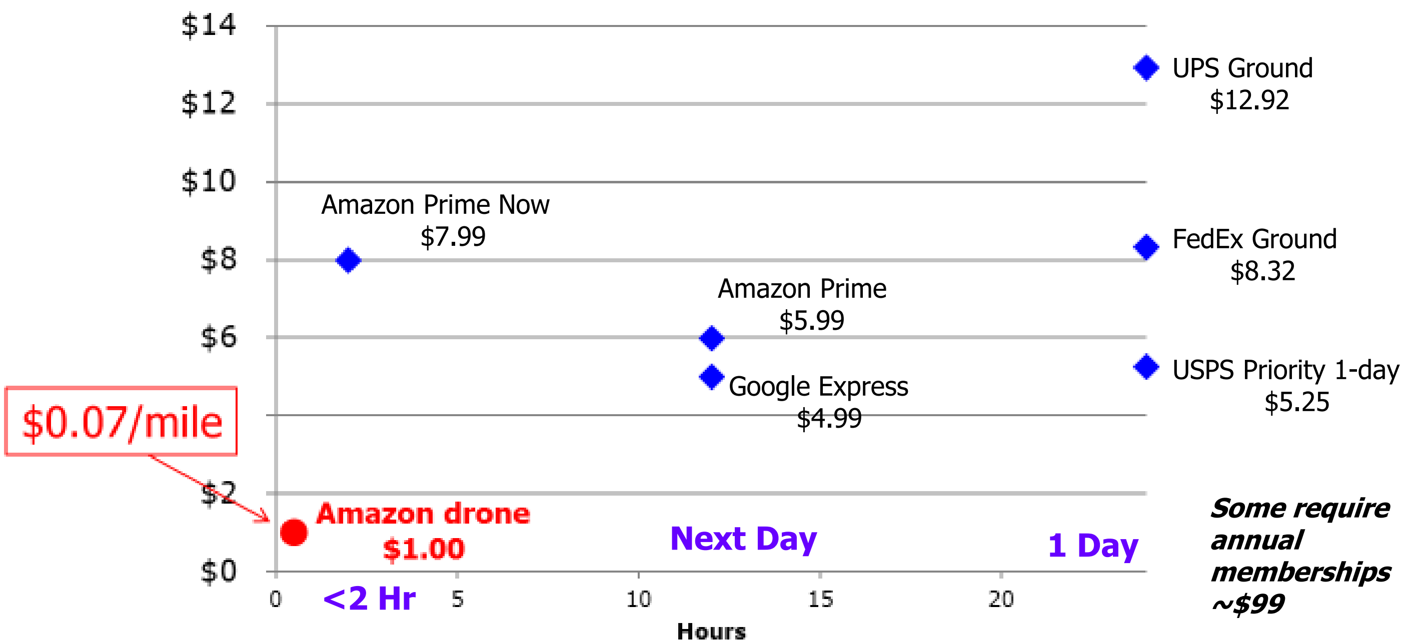
# Original Motivation

1. Amazon ships >600 million packages/year amazon.com
2. 86% of Amazon's orders are <5 lbs.
3. 73% of customers are willing to pay for drone delivery
4. Amazon lost $7 billion in 2016 on shipping.




*Some require annual memberships ~$99*

Source: https://ark-invest.com/research/amazon-drone-delivery/

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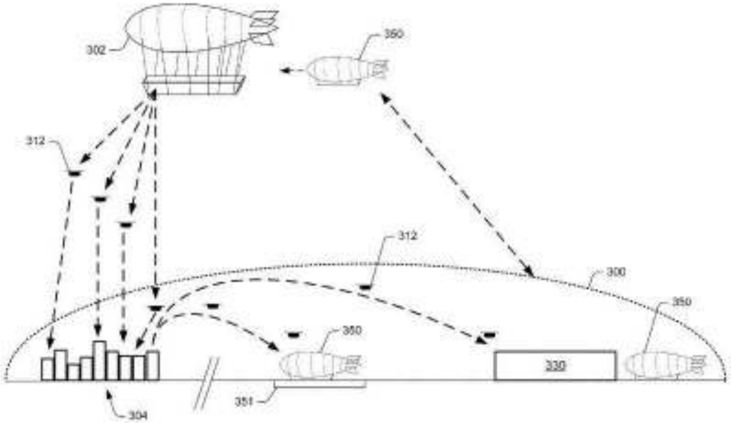
# Outline

Part 1. <u>Commercial</u> Drones and Drone Applications

Part 2. Strategic Continuous Approximation Model for Delivery with Drones and Trucks

Part 3. Research Opportunities for Locational Analysis and Related Problems with Drones

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# Part 1: Aerial Drones = UAVs

- UAVs = Unmanned Aerial Vehicles
  - ➢ vehículo aéreo no tripulado? (or UAV)

➢ Rotocopter

# Ground Drones

- Ground vehicles (UGV) – home delivery


# Other Drones

- Sea vehicles/vessels –
  - USV (Unmanned Surface Vessel), AUV (Autonomous Underwater Vehicle) or UUV (Unmanned Undersea Vehicle)
  - Data collection
  - Maritime security and mine counter-measures

# Delivery Applications

- Delivery to discrete "customers"
  - ➢ Packages
  - ➢ Healthcare and humanitarian aid
    - – Ongoing operations
      - ➢ Blood, medications, vaccines, organs, defibrillators
    - – Disaster response
      - ➢ Food, water, medicines, parts, etc.
- Area coverage – crop spraying

# Sensing and Surveillance Applications

- Cover a region, network or set of points - or follow targets
  - Precision agriculture
  - Fire protection
  - Security
  - Disaster response and search
  - Wildlife monitoring and tracking
  - Imaging:
    - Filming
    - Real estate

# Aerial Delivery Drones

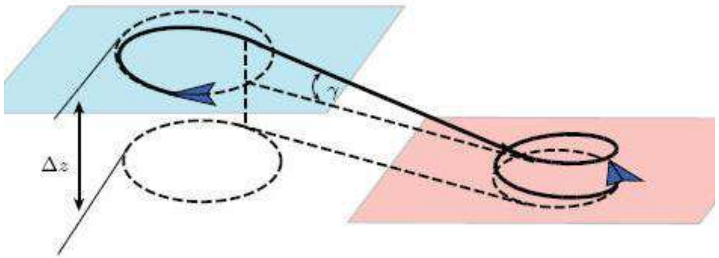
- Many different types!
  - Speed: up to 150 km/hr
  - Range: 10 – 150 km (>1000 km for military drones)
    - Depends on speed, payload, aeronautics, battery or fuel
  - Battery life: 18 – 60 minutes (weeks for military drones)
  - Payload capacity: 0.5 – 15 kg
  - Cost: $1000 - $4000; Battery cost: $200
  - Delivery stop time: 30 – 60 secs
  - Operating cost per mile: $0.01 - $5

- Performance depends on:
  - Type of drone
  - How it is operated (speed, altitude)
  - Environment - weather (temperature, humidity, rain, etc.), wind, elevation…

# Drone Activities – Part 1

1. **Take off**: Vertical, runway, catapult

2. **Fly**: How to model?
   - Fixed wing, Rotary wing, Rotocopter
   - Dubins Path vs full range of motion



3. **Carry** a payload: How heavy?

# Drone Activities – Part 2

4. **Sense**
5. **Deliver**: (not for Sensing and Surveillance)
    - **Land** and release (then must take-off)
    - Lower via **tether**
    - Drop via **parachute**

6. **Land**: Vertical, runway, airbag
7. **Recharge**/refuel (extends range)

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# Use drones when…

- They allow **better service** and/or **lower cost** than alternatives
  - ➢ Allows high speed (fast) deliveries
  - ➢ Reduces cost (and improves safety) by removing human operators
- Alternatives are not available:
  - ➢ Ground travel is limited by infrastructure, congestion, etc.
  - ➢ No roads, indirect roads, No working vehicles (trucks, motorcycles, etc.)

***Only $\frac{1}{3}$ of Africans live within 2 km of a road that functions year round***

# Global Healthcare

- Zipline in Rwanda delivers blood in rural Rwanda
  - Makes rare blood types widely and quickly available to 21 hospitals (8 million people)
  - Transports 20% of Rwanda’s blood supply outside Kigali
  - Order via text, packed in minutes
  - Delivers up to 80 km away
  - 500 deliveries/day, 24/7, in all weather
  - Expanding to Tanzania, where they plan 2000 drone deliveries per day!

zipline

# Healthcare Examples

- Defibrillators delivery in the Netherlands
  - In 4.6 $mi^2$ region, drones arrive in ~1 min vs 10 min by road
  - Increased chance of survival from 8% to 80%!

- Clinic in rural Virginia (US) operates 1 weekend each year serving 3000 patients
  - Drones flew medicines from a nearby airport in 3 min. vs 90 min. by road from a pharmacy 35 miles away.

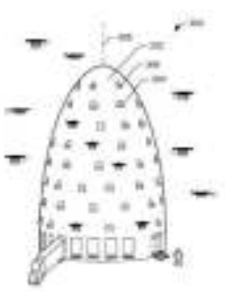
# Hybrid (Tandem) Operations

- Use trucks (or other vehicles) and drones together
- Trucks can launch and/or recover drones away from the depot

- Hybrid operations allow exploiting the advantages of each vehicle:
  - Drones: High speed and direct (straight line) travel
  - Trucks: High payload and can extend the range of service as a launch/recovery platform


# Modeling Problems with Drones

- Facilities to locate:
  - Depots, Launch points, Recovery/landing points, and Recharge points, Drone hubs?
- Travel:
  - Trucks: travel on road network using a particular metric
  - Drones: travel in straight lines; Dubins paths?
- Drones:
  - Range is limited (expressed in distance or time)
  - May make 1 or >1 delivery per trip
- Demand:
  - Delivery is usually one item per customer
  - Surveillance and sensing is coverage (e.g., arc routing)
  - Customers (or items) have a service (delivery) time limit
  - Some customers may not be served by drones
- Other vehicles: Are they "allowed" and can they also make deliveries?



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# Academic Research

- Quite a bit of research from robotics and engineering, especially in "path planning" (routing)
  - Often algorithms are not very sophisticated
  - Much focus on military & defense applications

- Growing research from the OR community
  - Most focuses on routing (extending TSP and VRP models)
  - Link to electric (ground) vehicle refueling research
  - Networks special issue (Agatz and Campbell) and INFORMS meeting
- Key OR Problems: <u>Routing</u>, <u>Location</u> and <u>Network Design</u>

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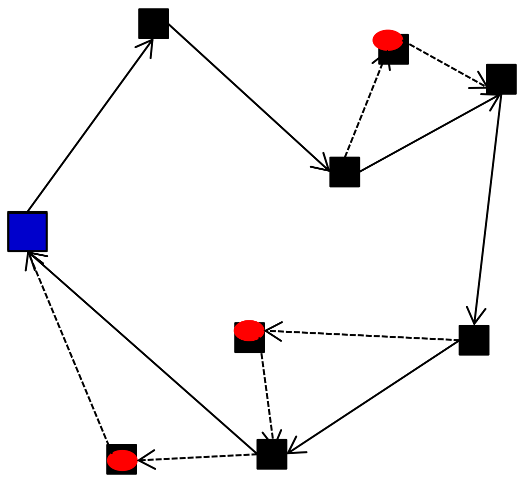
# Academic Research

- Drone-only delivery can be modelled as one-to-many distribution systems or as vehicle routing problems.
- Growing research specific to drone delivery.
- Hybrid truck-drone delivery is new – and only a few papers address logistics aspects.
  - Lin *Comp & OR 2008*, 2011: hybrid truck-foot courier.
  - Mathew et al. *IEEE Trans on Auto. Sci. & Eng*. 2015 (Location)
  - Murray and Chu, *Trans Res C* 2015: "flying sidekick".
  - Ha et al. 2015, 2016; Ponza 2016; Ferrandez 2016.
  - Wang et al. *Opt Ltrs* 2016: worst case analysis.
  - Dorling et al. 2016: energy consumption.
  - Carlsson and Song *Man. Sci.* 2017: Continuous Approx.
  - Otto et al. 2017: Survey paper

# Murray and Chu 2015

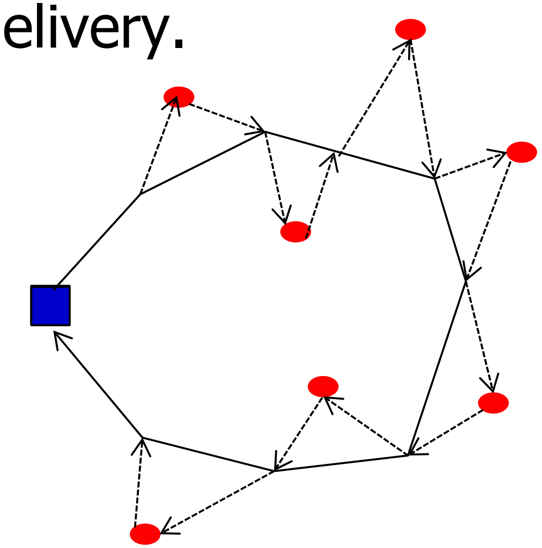
- Treated as a variation of a VRP, with coordination of recovery time for drone at the truck.
- One drone per truck is launched and recovered only at customer stops.
  - Drone must return to truck at a stop different from where it was launched.
- Two large MILP formulations.
  - Minimize time of return to the depot.
- Solved with heuristics:
  - Build a truck route (TSP).
  - Reassign stops to the drone.
- Also considers serving nearby customers by drone directly from the depot.

"Flying sidekick"

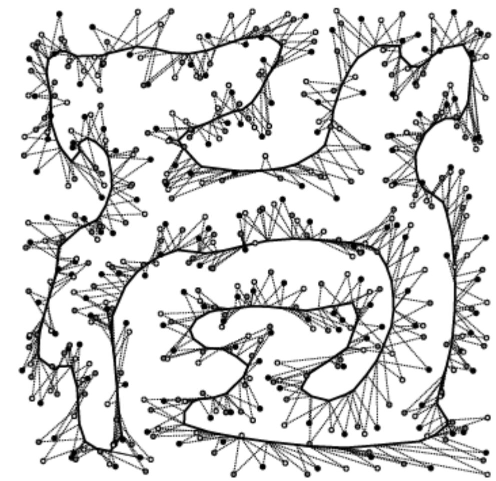


# Carlsson and Song 2017

- Continuous approximation model to provide asymptotic bounds on route to minimize time of last delivery.
  - Extends Beardwood, Halton, Hammersley theoretical TSP tour length analysis to drones.



- One or more drones per truck are launched and recovered from a truck that makes **no** deliveries.
  - Drone may return to truck at the same location  from where it was launched.
- Simulation modeling in Los Angeles area to verify results.
- Focus on relative speeds of truck and drones.



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# Industry Research

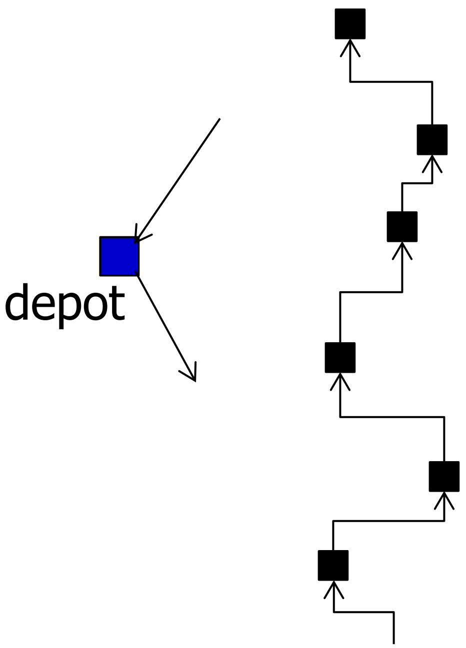
- **Very active** – and **very dynamic** area of research by industry and academic partners...
- Difficult to get details and to keep up with current developments (promotional materials, patents, industry reports, etc.).
- Existing cost analyses **vary widely**, but suggest using drones may be **very efficient**!

# Part 2: Our Focus

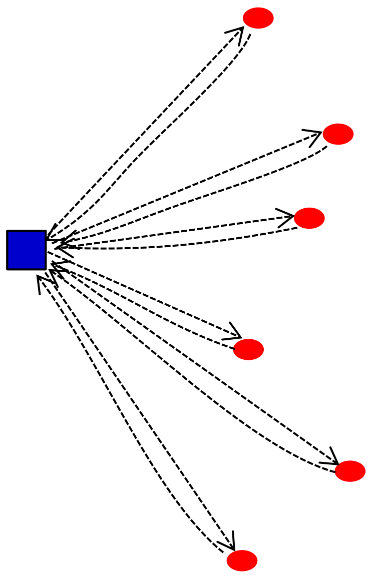
- **Strategic analysis** of hybrid **truck-drone delivery systems**.
  - Under what conditions (for customers and drones) does it make sense to use drones?
- Compare truck-drone delivery to drone-only and truck-only delivery.
- Focus on **logistic and operational aspects**, not regulatory, legal or technical details.

# Service Options

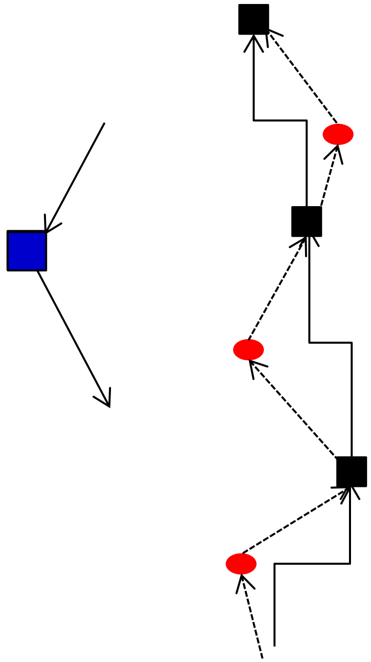
**Truck Delivery**
L1 metric




**Drone Delivery**
L2 metric



**Truck-Drone Delivery**
L1 & L2 metric



# Our Approach…

- Use **Continuous Approximation (CA) models** to derive general insights (instead of extending TSP and VRP models).
  - "Continuous approximation models in freight distribution management", Franceschetti, Jabali, Laporte, *TOP* 2017.


- Design general minimum cost system for truck-drone delivery, where demand is a **continuous density** (# of customers per sq. mile) over the service region.
  - Derive expected travel cost expressions based on key parameters of the setting and drones.
  - Analytically optimize equations to find minimum cost designs.

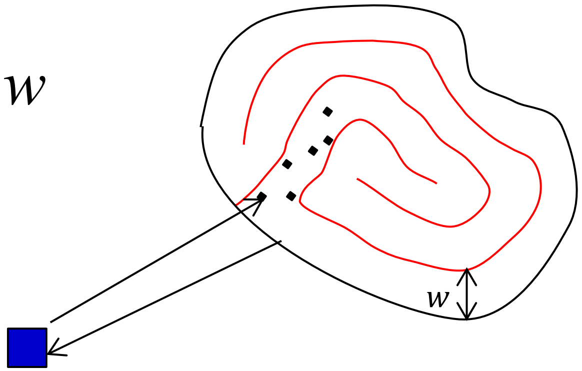
# Analyses

1. Compare hybrid truck-drone delivery to truck-only delivery.
   - In what situations is truck-drone delivery useful?
   - How does this depend on the density of customers and key drone operating parameters?
   - How useful are multiple drones per truck?

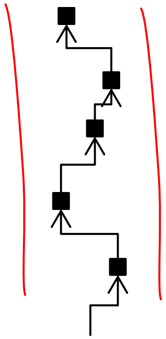
2. How should a region be served?
   - Divide a region into sub regions where each strategy (truck-only, drone-only, truck-drone) is best?
   - How does this depend on the density of customers and key drone operating parameters?

# Basic Continuous Approximation Model

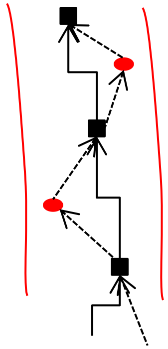
- Truck travels along a swath of width $w$ through the service region visiting customers in order (Daganzo 1984).




- Spatial density of customers is $\delta$.
- Model travel with L1 (rectilinear) distance, so truck has horizontal and vertical travel along the swath.



- Optimize swath width using calculus.
- Similar idea with **truck-drone delivery** along the swath…where drone travel is modelled with L2 distance.



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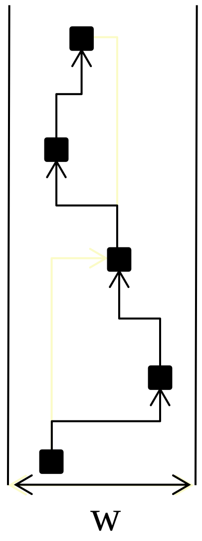
# Modeling Truck Travel: L1 distance

- Density of customer stops (#/mile$^2$): $\delta$
- Expected horizontal travel distance per stop = $\frac{w}{3}$
- Expected vertical travel distance per stop = $\frac{1}{\delta w}$
- Expected total distance per stop = $\frac{1}{\delta w} + \frac{w}{3}$
- Optimal width for truck alone: $w^* = \sqrt{\frac{3}{\delta}}$
- Truck stop cost (per delivery) = $s_t$
- Expected truck-only cost per delivery:

$$E_{to} = c_t \left\{ \frac{2}{\sqrt{3\delta}} \right\} + s_t$$

Truck cost per mile

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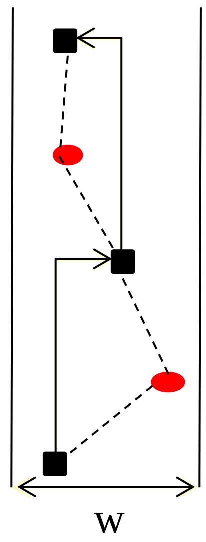
# Modeling Truck-Drone Travel

- Truck L1 travel per stop:
  - Expected horizontal travel distance = $\frac{1}{2}\frac{w}{3} = \frac{w}{6}$
  - Expected vertical travel distance = $\frac{1}{2}\frac{2}{\delta w} = \frac{1}{\delta w}$
  - Truck stop cost = $s_t$




- Drone L2 travel per stop:
  - Expected distance = $\sqrt{\left(\frac{w}{3}\right)^2 + \left(\frac{1}{\delta w}\right)^2}$
  - Marginal drone stop cost relative to truck stop cost = $s_d$

Expected total truck-drone cost per delivery:

$$E_{td} = c_t\left(\frac{w}{6} + \frac{1}{\delta w}\right) + c_d\sqrt{\left(\frac{w}{3}\right)^2 + \left(\frac{1}{\delta w}\right)^2} + \frac{1}{2}s_d + s_t$$

Drone cost per mile

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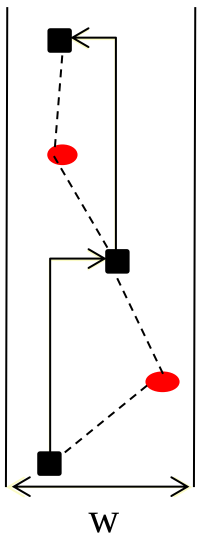
# Optimal Swath Width

- Optimal width for truck travel alone: $w = \sqrt{2}\sqrt{\frac{3}{\delta}}$
- Optimal width for drone travel alone: $w = \sqrt{\frac{3}{\delta}}$
- Optimal width for truck drone travel

$$w^* \cong \frac{\left(\sqrt{2}+2\frac{c_d}{c_t}\right)}{1+2\frac{c_d}{c_t}}\sqrt{\frac{3}{\delta}} = k^*\sqrt{\frac{3}{\delta}}$$




Expected total truck–drone cost per stop

$$= \frac{1}{\sqrt{3\delta}}\left\{c_t\left[\frac{k^*}{2}+\frac{1}{k^*}\right] + c_d\sqrt{k^{*2}+\frac{1}{k^{*2}}}\right\} + \frac{1}{2}s_d + s_t$$

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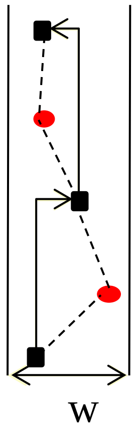
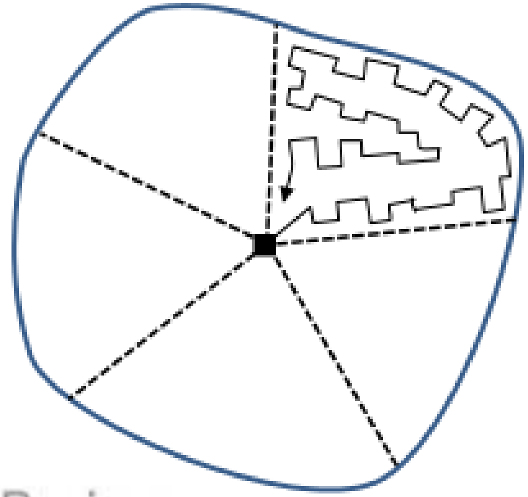
# Linehaul Travel

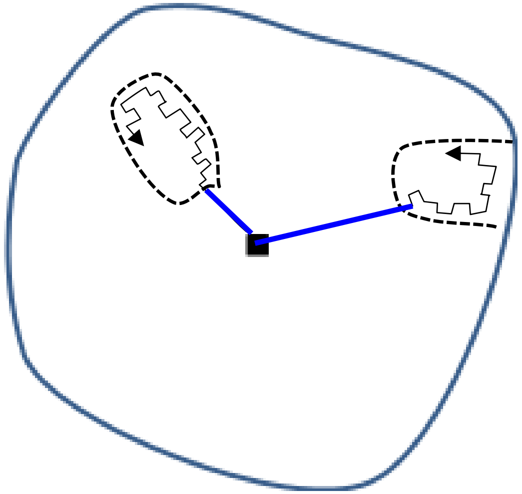
- If truck-drone route is a small fraction of the service region, then there is a linehaul travel to the area of the route.
- Depends on the size of the region!




*With five routes, each route is like a TSP tour.*

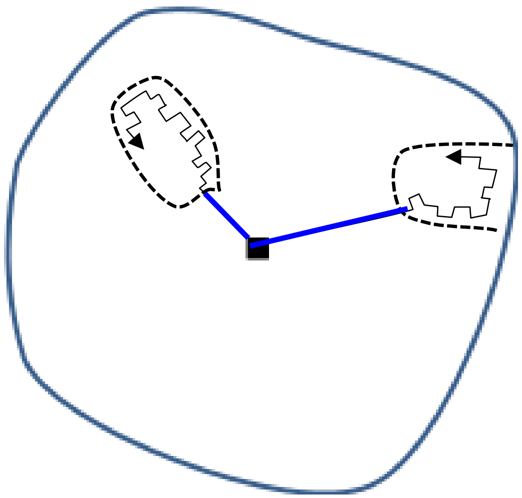


*With many routes, there is linehaul distance to and from the start of the route.*



# Linehaul Cost

- ρ = expected distance from the depot to a random point in the region of area $A$
  - In a circular region with a depot at the center, $\rho = \frac{2}{3}\sqrt{A/\pi}$.
- For an elongated delivery zone in the region of area $A$, the expected round-trip truck linehaul cost per delivery to the **edge** of the zone $= c_t\left(\frac{2\rho}{m} - \frac{1}{2\delta w}\right)$.
- $m$ = total number of deliveries on the route.



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# Number of Stops and Route Length

- Route time $\leq T$.
- Assume drones are fast enough that truck does not wait for drones…
- Set *Truck delivery time + Linehaul time* $= T$.

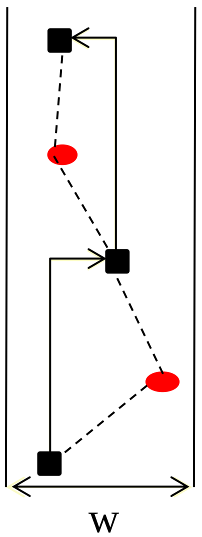
➢ Solve for # of deliveries $m_{td}$

$$m_{td} = \frac{T - 2\rho c'_{tl}}{c'_t \left[\frac{w}{6} + \frac{1}{\delta w}\right] - c'_{tl}\frac{1}{2\delta w} + \frac{1}{2} s'_t}$$

1/Truck delivery speed

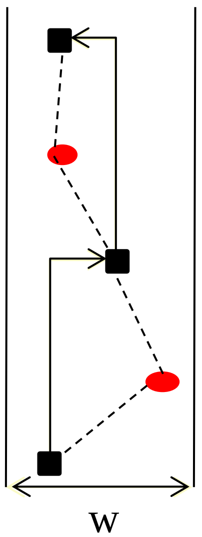
1/Truck linehaul speed

Truck delivery stop time



# Key Problem Parameters

- Expected total cost depends on:
  - Truck and drone operating cost per mile: $c_t$, $c_d$
  - Marginal drone delivery cost per stop (may be positive or negative): $s_d$
  - Truck cost per stop: $s_t$
  - Density of customer stops: $\delta$
  - Area served: $A$, which determines $\rho$
  - Number of stops per route: $m_{td}$




Expected total truck-drone cost per stop with linehaul:

$$E_{td} = \frac{c_t}{\sqrt{3}}\left(1+\sqrt{2}\frac{c_d}{c_t}\right)\sqrt{\frac{1}{\delta}} + c_t\frac{2\rho}{m_{td}} + \frac{1}{2}s_d + s_t$$

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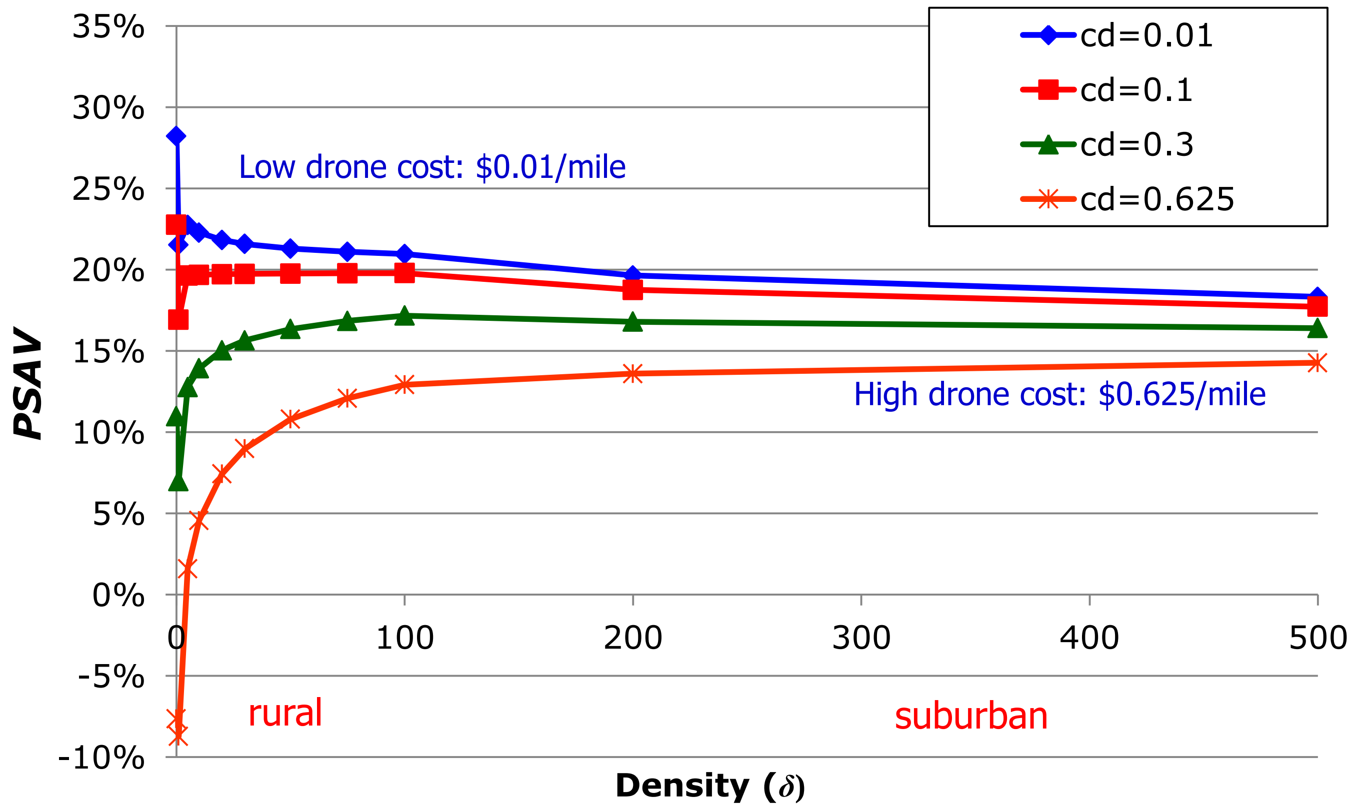
# Cost Savings per Delivery with 1 Drone per Truck: 4 Levels of Drone Operating Cost

- Percentage savings per delivery ***PSAV*** for truck-drone delivery can be large (15-20%), and generally decrease with density of deliveries.

$c_t = \$1.25/mile$
$s_d = -\$0.1$
$A = 2000\ mi^2$




*Average US density of households = 33/mile² or 128/mile² in metro areas.*

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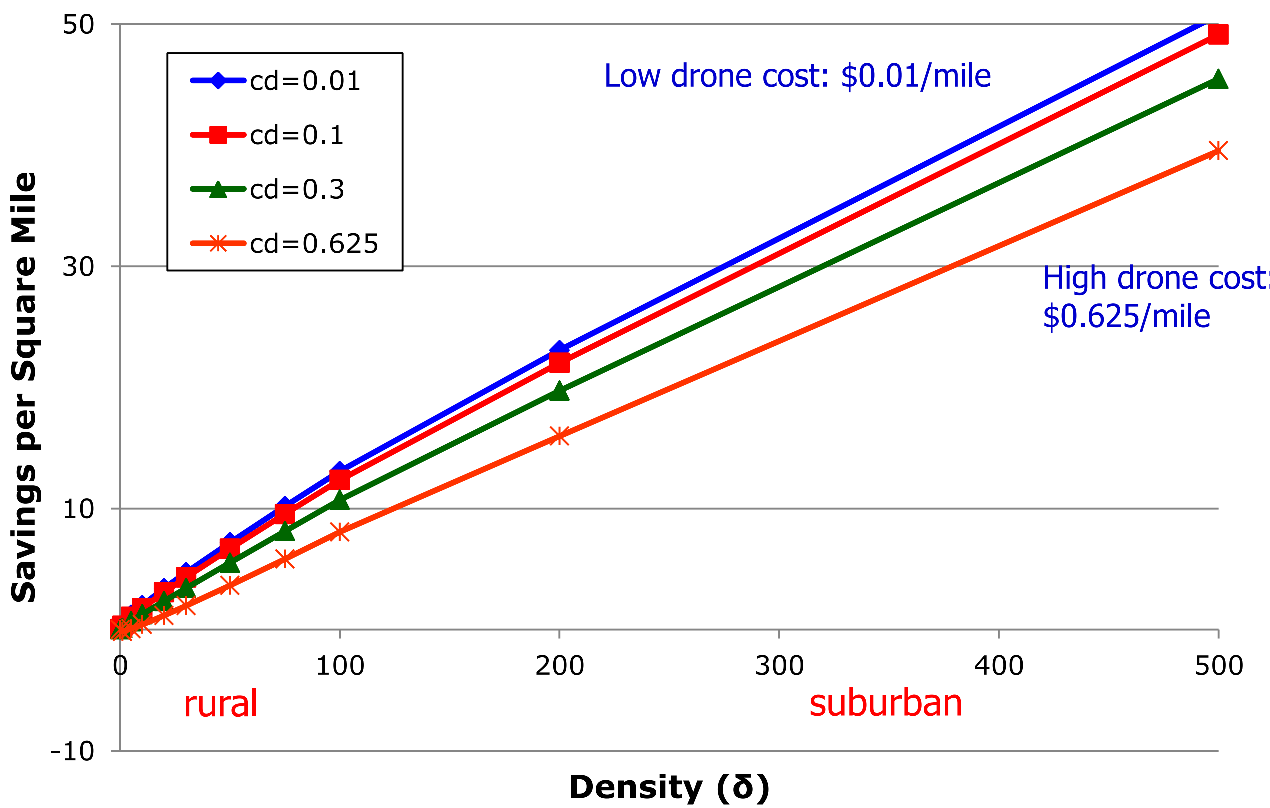
# Cost Savings per Sq. Mile with 1 Drone per Truck: 4 Levels of Drone Operating Cost

- Savings <u>per square mile</u> for truck-drone delivery can be large ($50/mi²=18%), and *increase* with density of deliveries.

$c_t = \$1.25/mile$
$s_d = -\$0.1$
$A = 2000\ mi^2$

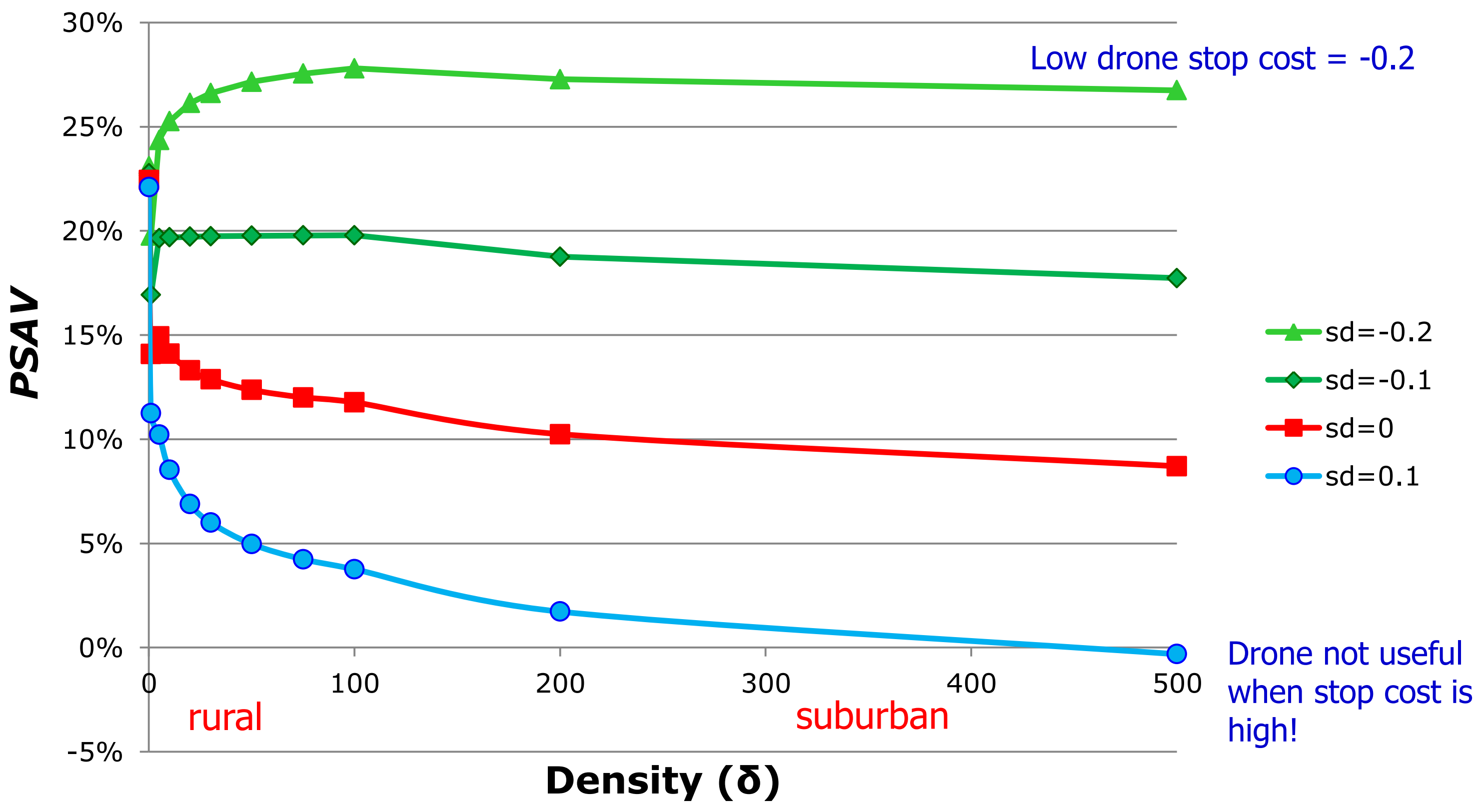



*Average US density of households = 33/mile² or 128/mile² in metro areas.*

# Cost Savings per Delivery with 1 Drone per Truck: 4 Levels of Drone Stop Cost

- Percentage savings per delivery for truck-drone delivery decreases with drone marginal stop cost; generally decreases with density of customers.

$c_t = \$1.25$
$c_d = \$0.1$
$A = 2000\ mi^2$

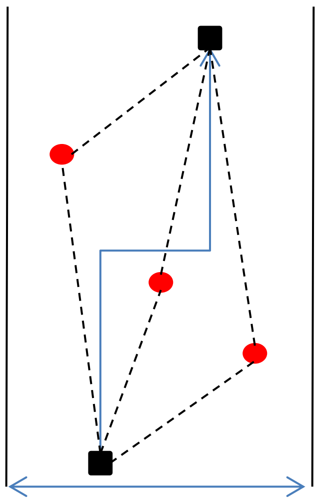


# Summary of Findings: 1 Drone per Truck

1. Hybrid truck-drone delivery can provide **large savings** with drones used optimally.
2. For reasonable parameter values drones should be used a large amount – where feasible.
3. Attractiveness of drones depends strongly on drone operating cost, marginal drone stop cost and density of stops.
4. Savings with drones increases with density of customers, though savings per delivery may decrease.

# Multiple Drones per Truck

- n drones are launched and recovered at the truck.
- Expected cost now depends on number of drones n, as well as: $c_t$, $c_d$, $s_d$, $s_t$, $\delta$, $A$, $w$, and $m$.




Expected total cost per delivery: $E_{td}(n) =$

$$\underbrace{\left\{c_t\left[\frac{1}{n+1}\frac{w}{3}+\frac{1}{2\delta w}\right]}_{\text{Truck}} + \underbrace{c_d\frac{2n}{n+1}\sqrt{\left(\frac{w}{3}\right)^2+\left(\frac{n+1}{2\delta w}\right)^2}\right\}}_{\text{Drone}} + \underbrace{c_t\frac{2\rho}{m_{td}}}_{\text{Linehaul}} + \underbrace{\frac{n}{n+1}s_d + s_t}_{\text{Stop costs}}$$

Swath width $w^* = f\left(n, \frac{c_d}{c_t}\right) \times \sqrt{\frac{3}{\delta}}$

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# All Models

| $F$ | Linehaul Travel | Optimal or Near-optimal Swath Width | Expected Cost |
|---|---|---|---|
| 0.5 | Yes | $\sqrt{\frac{3}{\delta}}$ | $c_t\sqrt{\frac{1}{3}}\left(1+\sqrt{2}\frac{c_d}{c_t}\right)\sqrt{\frac{1}{\delta}}+c_t\frac{2\rho}{m_{td}}+\frac{1}{2}s_d+s_t$ |
| > 0.5 | Yes | $\sqrt{\frac{n+1}{2}}\sqrt{\frac{3}{\delta}}$ | $c_t\sqrt{\frac{2}{3}}\frac{1+\sqrt{2}n\frac{c_d}{c_t}}{\sqrt{n+1}}\sqrt{\frac{1}{\delta}}+c_t\frac{2\rho}{m_{td}}+\frac{n}{n+1}s_d+s_t$ |
| ≥ 0.5 | No | $\sqrt{n+1}\left[\frac{1+\sqrt{2}n\frac{c_d}{c_t}}{1+2n\frac{c_d}{c_t}}\right]\sqrt{\frac{3}{\delta}}$ | $c_t\left[\frac{1}{n+1}\frac{w}{3}+\frac{1}{\delta w}\right]+c_d\frac{2n}{n+1}\sqrt{\left(\frac{w}{3}\right)^2+\left(\frac{n+1}{2\delta w}\right)^2}+\frac{n}{n+1}s_d+s_t$ |
| < 0.5 | Yes | $\frac{\sqrt{n+1}+2\frac{c_d}{c_t}}{\sqrt{2}+2\frac{c_d}{c_t}}\sqrt{\frac{3}{\delta}}$ | $c_t\left[\frac{1}{n+1}\frac{w}{3}+\frac{1}{2\delta w}\right]+2c_d\frac{n}{n+1}\sqrt{\left(\frac{w}{3}\right)^2+\left(\frac{1}{\delta w}\right)^2}+c_t\frac{2\rho}{m_{td}}+\frac{n}{n+1}s_d+s_t$ |
| < 0.5 | No | $\frac{\sqrt{n+1}+2\frac{c_d}{c_t}}{1+2\frac{c_d}{c_t}}\sqrt{\frac{3}{\delta}}$ | $c_t\left[\frac{1}{n+1}\frac{w}{3}+\frac{1}{\delta w}\right]+2c_d\frac{n}{n+1}\sqrt{\left(\frac{w}{3}\right)^2+\left(\frac{1}{\delta w}\right)^2}+\frac{n}{n+1}s_d+s_t$ |

$F$ = fraction of stops by drones

Swath width $w^* = f\left(n,\frac{c_d}{c_t}\right)\times\sqrt{\frac{3}{\delta}}$

# Data for Drone Modeling

- What are appropriate values for:
  - Truck operating cost per mile: $c_t$
  - Drone operating cost per mile: $c_d$
  - Marginal drone delivery cost per stop (positive or negative): $s_d$
  - Number of stops per route: $m_{td}, m_{to}$
  - Density of customer stops: $\delta$
  - Area served: $A$

# Costs for Drone Modeling

- From Ark Invest 2016:
  - 400 million packages/year are drone eligible for Amazon: <5 lbs and within 10 miles of a depot.
  - 30 deliveries per drone per day.
  - 40,000 drones and 90,000 batteries.
  - 6000 drone operators & 10-12 drones per operator.

| | Category | Annual cost | |
|---|---|---|---|
| Capital costs | Infrastructure | $50 million | |
| | Drones and batteries | $80 million | |
| Operating costs | Labor: 10-12 drones per operator | $300 million | |
| | Data bandwidth | $25 million | |
| | Maintenance and electricity | $25 million | |
| Total | | $1/delivery | **$0.07/mile** |

With 6 drones per operator: $1.60/delivery **$0.11/mile**

# Data for Drone Modeling

- Truck operating cost per mile: $c_t$ = \$1.25/mile
- Drone operating cost per mile: $c_d$ = \$0.01 to \$0.30/mile
  - Base case $c_d$ = \$0.10/mile
- Marginal drone delivery stop cost: $s_d$ = –\$0.20 to \$0.10/stop
- Number of stops per route based on 8 hour routes
- Density of customer stops: $\delta$ = 0.01 – 500/mile$^2$
- Area served: $A$ = 2000 mile$^2$


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# Illustration

- Models produce reasonable values for routes.

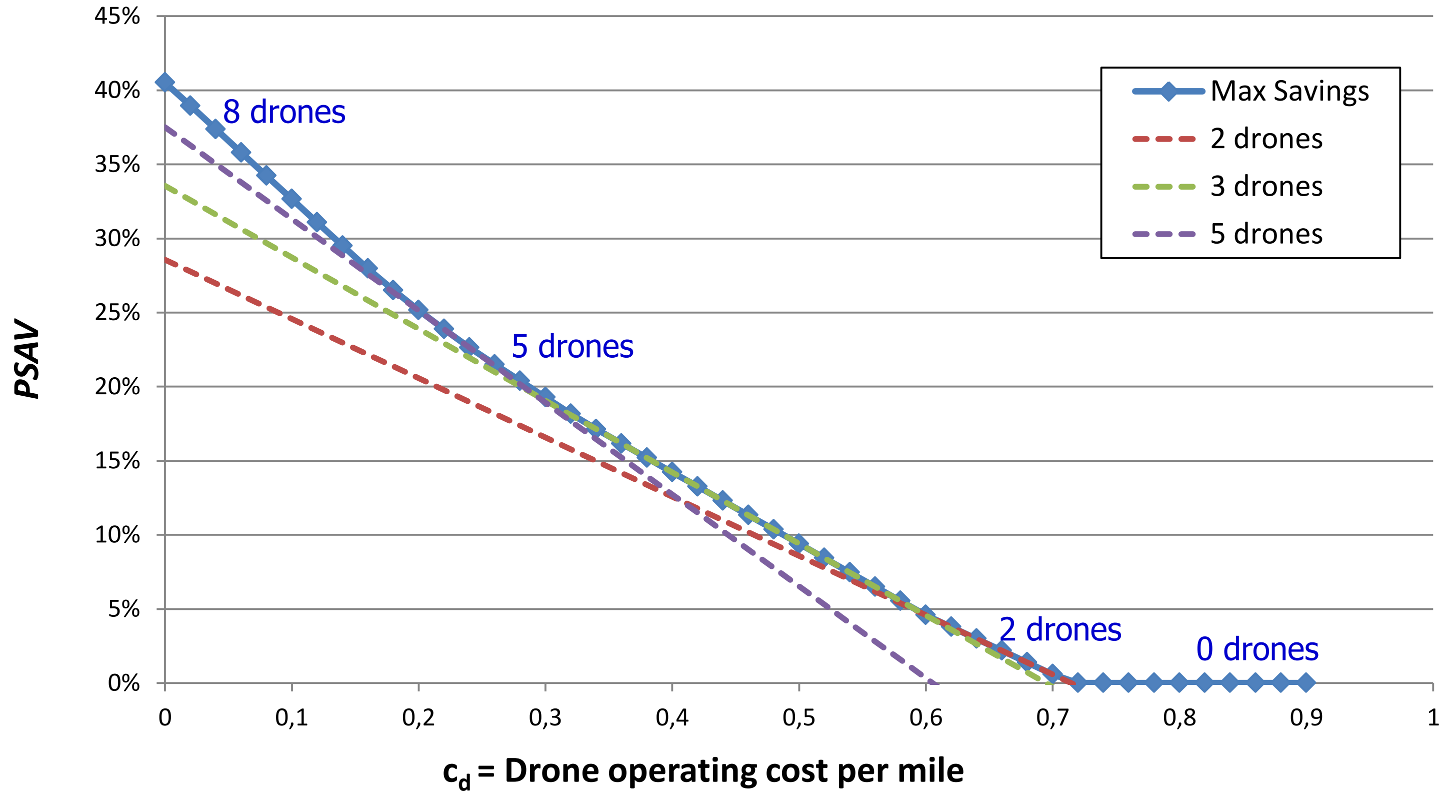
| | $\delta$ = 0.1/square mile rural | | | $\delta$ = 50/square mile suburban | | |
|---|---|---|---|---|---|---|
| $n$ | 0 | 1 | 2 | 0 | 1 | 2 |
| Swath width (miles) | 5.5 | 7.4 | 8.8 | 0.17 | 0.24 | 0.30 |
| Number of truck deliveries per route | 40.2 | 29.1 | 24.0 | 290.2 | 262.7 | 242.0 |
| Number of drone deliveries per route | 0 | 29.1 | 47.9 | 0 | 262.7 | 484.1 |
| Average truck route length (miles) | 146.6 | 150.3 | 152.0 | 71.8 | 80.5 | 86.0 |
| Average drone travel distance per drone delivery (miles) | - | 5.6 | 6.8 | - | 0.23 | 0.28 |
| Number of routes as a % of truck only routes | - | 69.0% | 55.8% | - | 55.2% | 40.0% |

- As delivery density increases, route length decreases, number of deliveries increases, and drone travel distance decreases.
- As # of drones per truck increases, route length increases slightly, number of deliveries increases, and drone travel distance increases a little.

# Percentage Cost Savings with 1-8 Drones per Truck

- Multiple drones per truck are beneficial; the optimal number of drones decreases with increasing drone cost.

$\delta = 10$
$s_d = 0$

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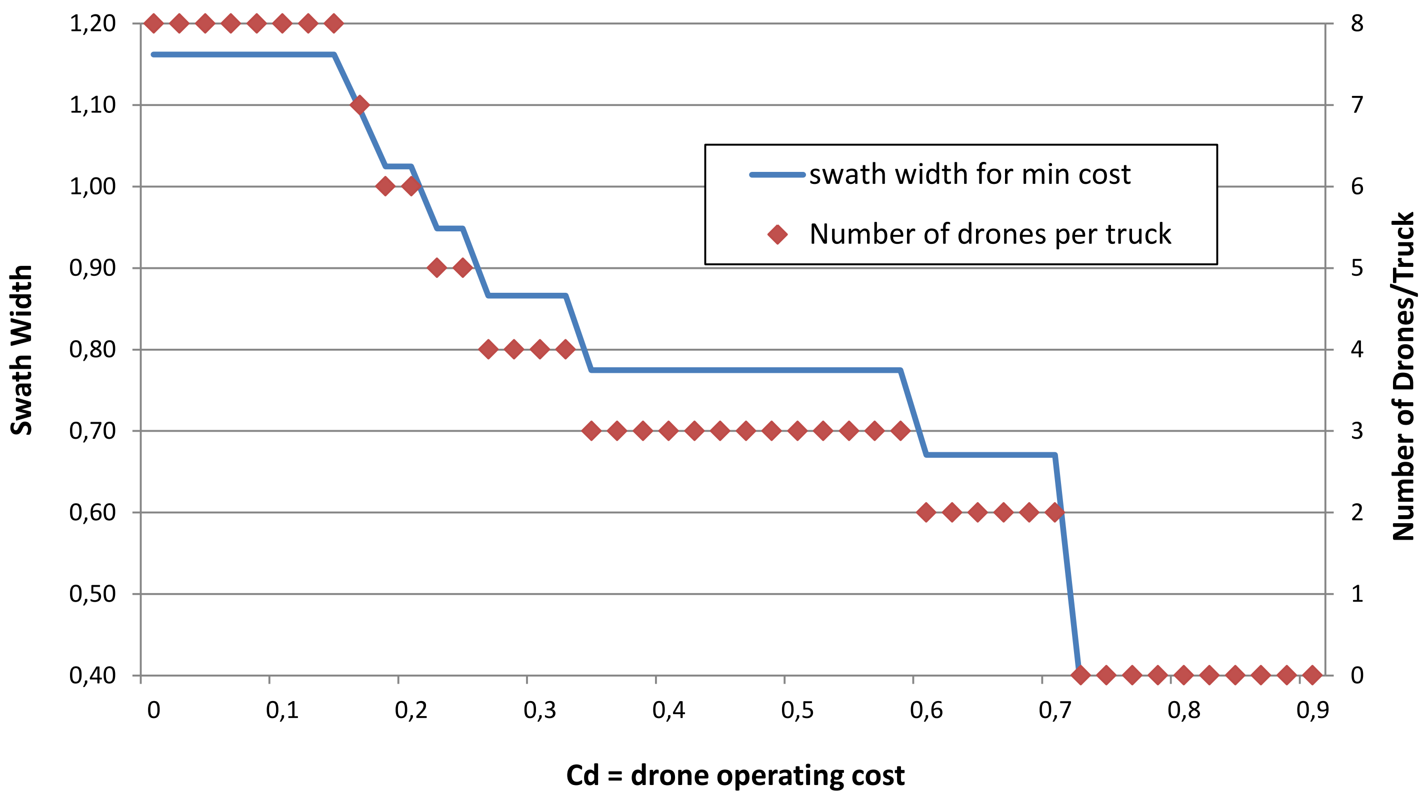
# Swath Width and # of Drones per Truck

- Swath width and # of drones per truck decrease as drone cost increases.

$\delta = 10$
$s_d = 0$

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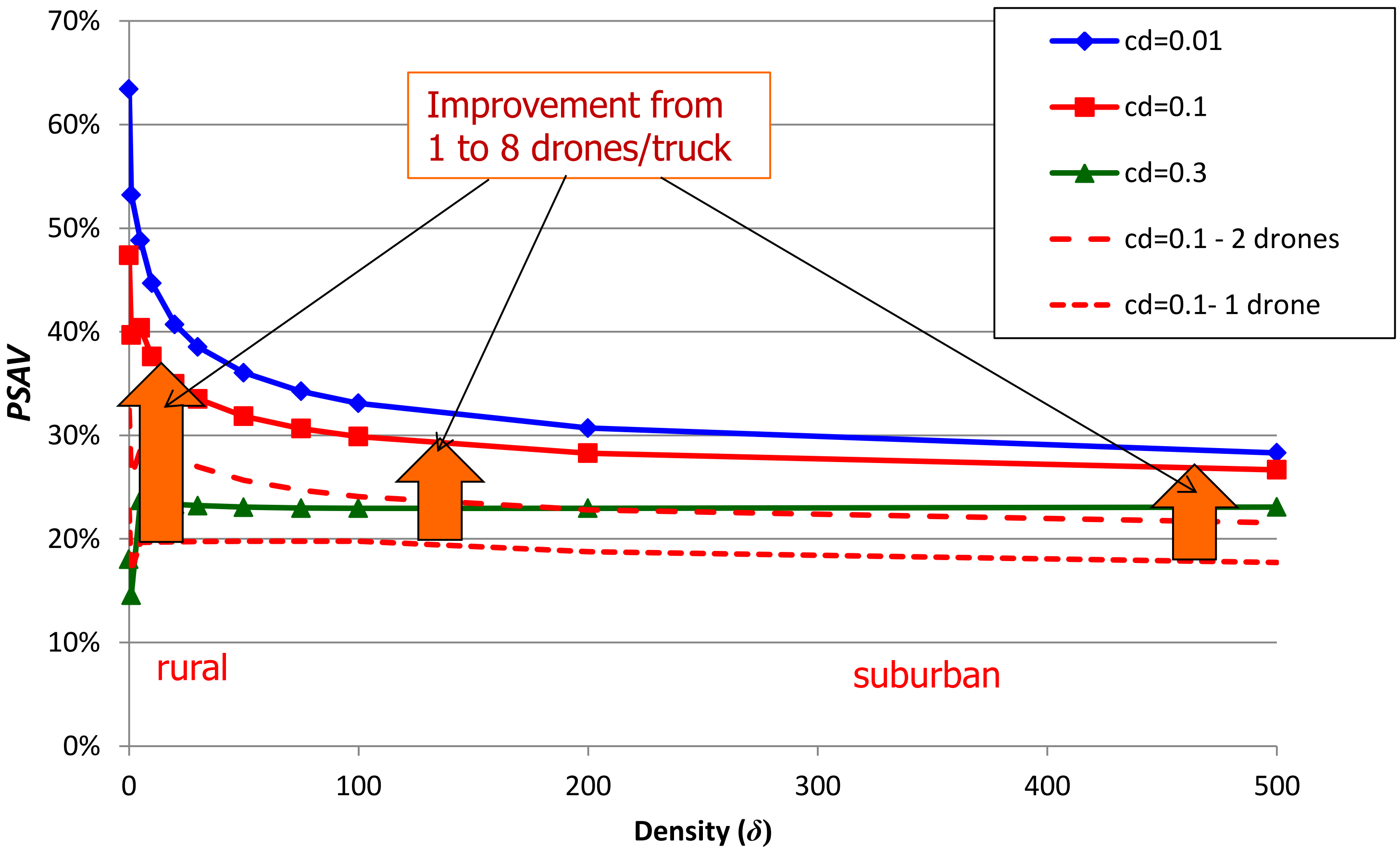
# Up to 8 drones/truck: Marginal drone stop cost = -0.1

- Savings per delivery are up to 63%, but decrease with density.

$s_d = -0.1$

Drone stops are **$0.10 less** expensive than truck stops

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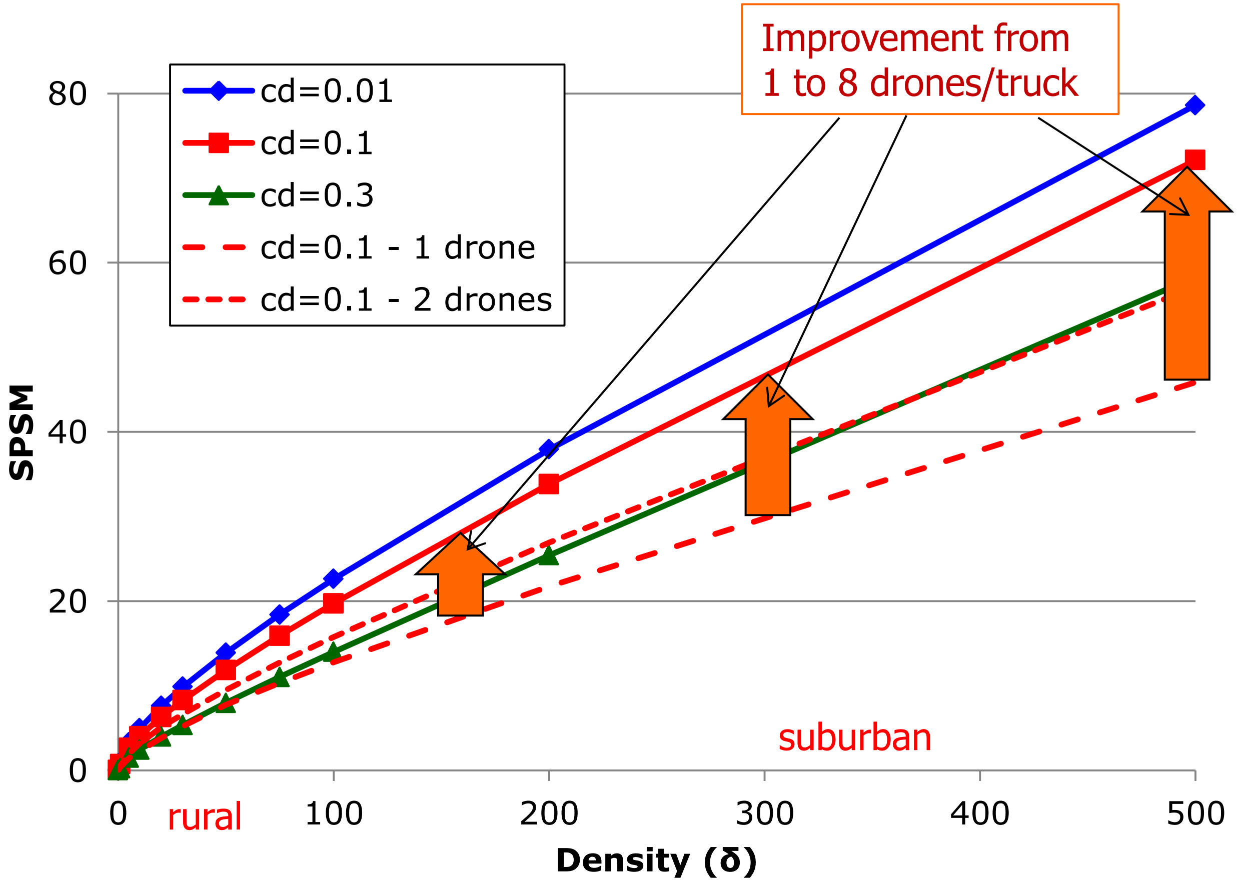
# Marginal Drone Stop Cost = – 0.1

- Savings per mile$^2$ increase with density…up to \$68/ mile$^2$ for $c_d$=0.1

$s_d = -0.1$

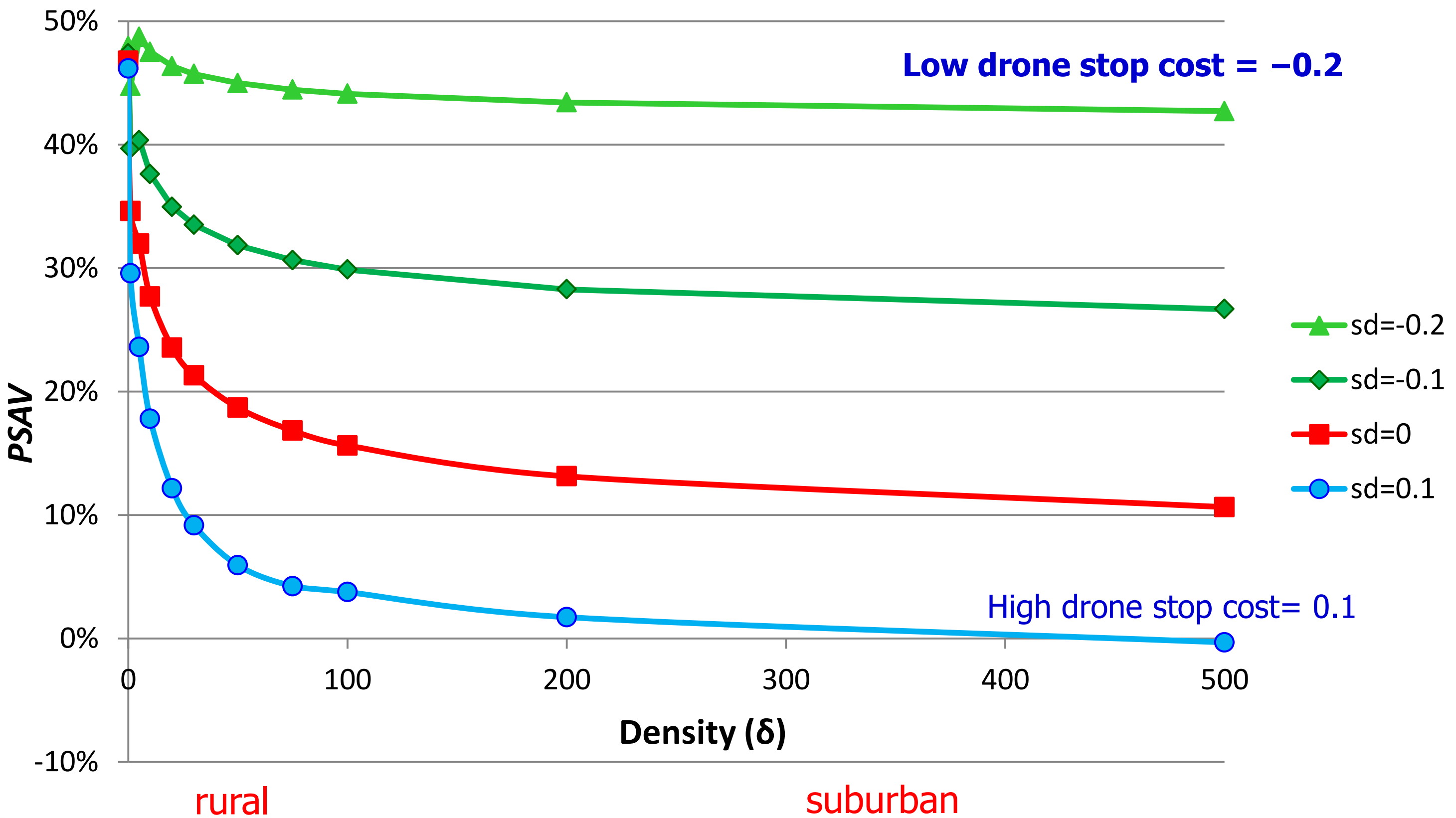
Drone stops are **\$0.10 less** expensive than truck stops



# Cost Savings for 4 Levels of Drone Stop Cost: $c_d$ = 0.1

- Multiple drones per truck are very beneficial.
- Savings remain large if drone stop cost is small.

$c_t = 1.25$
$c_d = 0.1$

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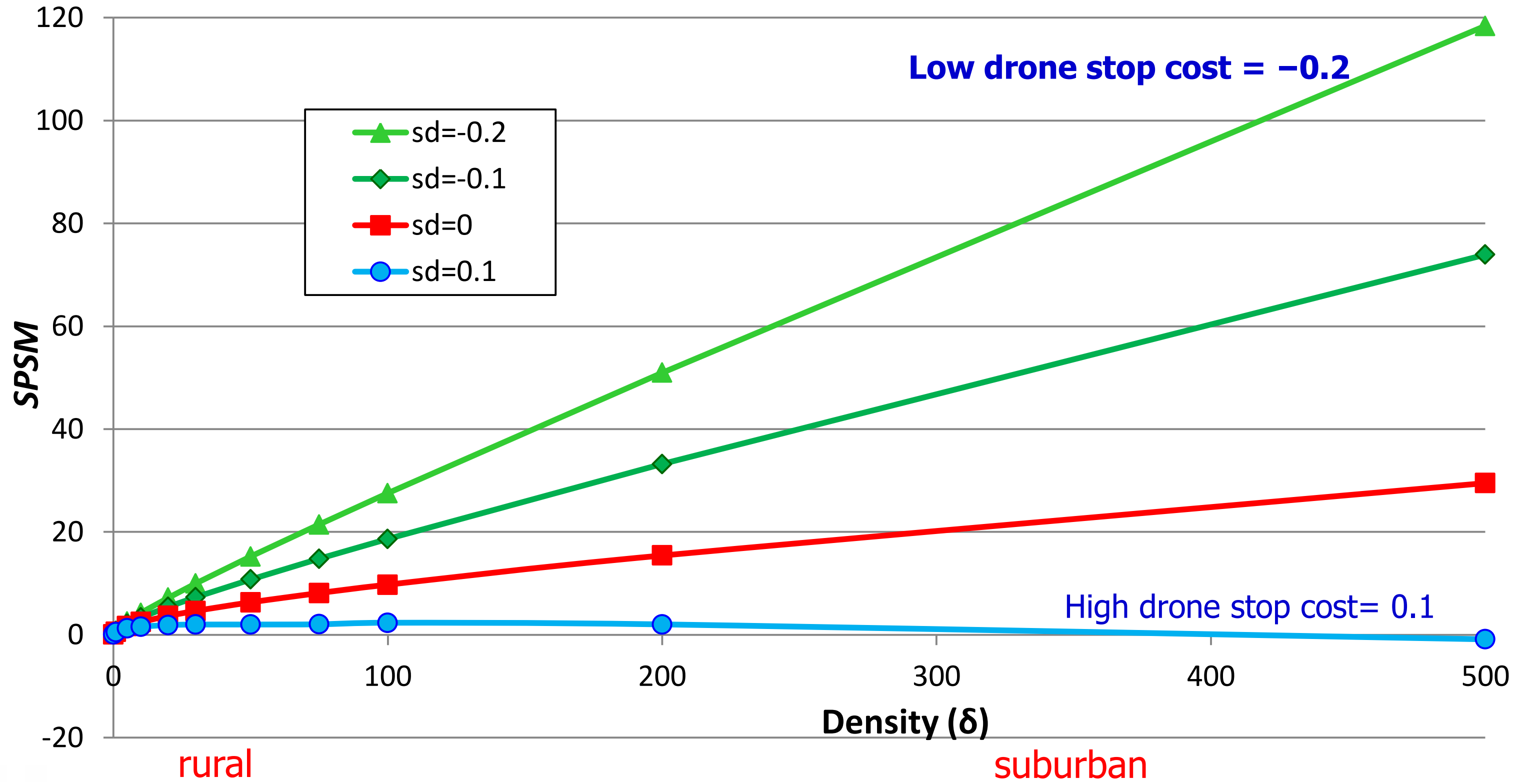
# Cost Savings for 4 Levels of Drone Stop Cost: $c_d = 0.1$

- Savings intensity ($/mile$^2$) increases with density and can be large!
- Multiple drones per truck are very beneficial! (up to $118/mile$^2$ ).

$c_t = 1.25$
$c_d = 0.1$

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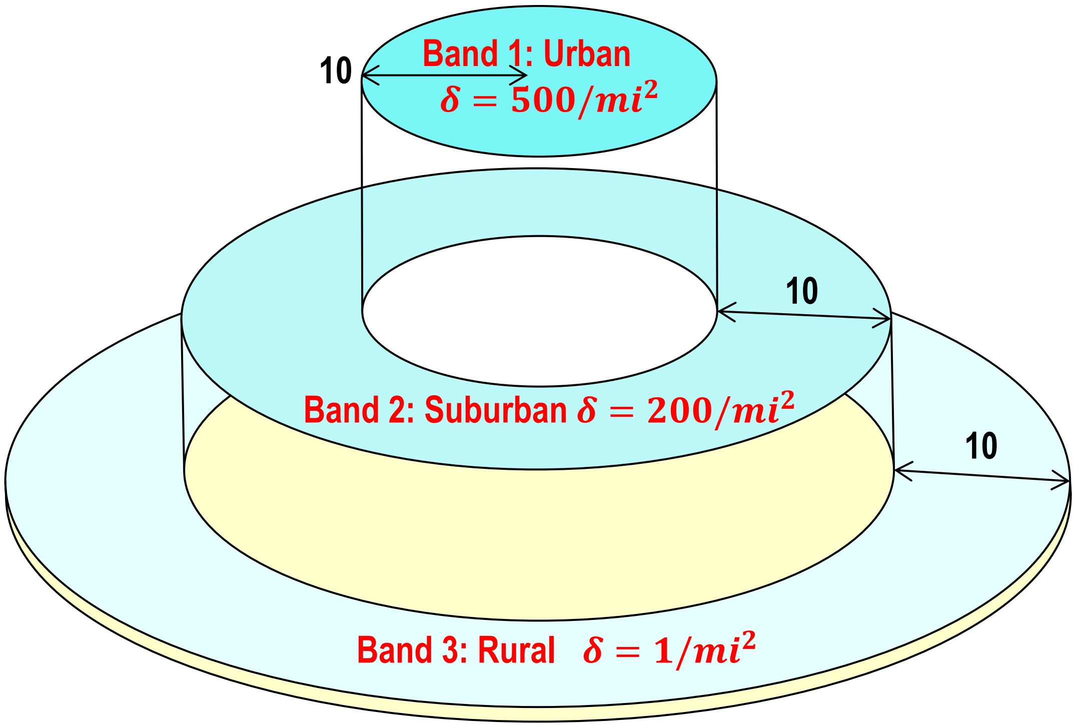
# Illustration with 3 Regions

- Consider a circular region of radius 30 miles with an urban core and a depot at the center.
- How would truck-drone delivery serve the region?

$c_t = \$1.25$
$c_d = \$0.3$
$s_d = -\$0.1$

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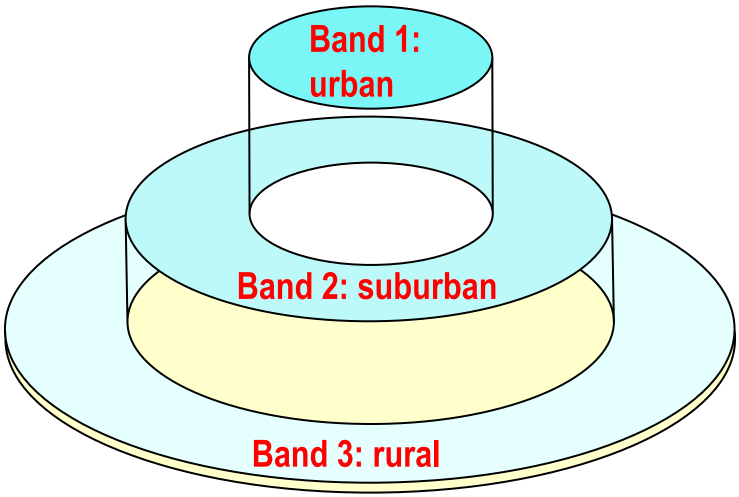
# Illustration

- Optimal drone use varies across the region!
- Greatest savings are not from the region with the greatest % savings per stop (PSAV).

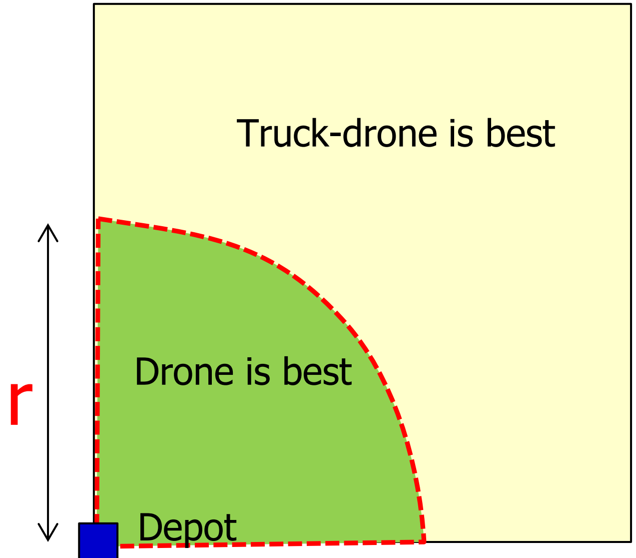
$c_t = \$1.25$
$c_d = \$0.3$
$s_d = -\$0.1$

| | Band 1<br>0-10 miles | Band 2<br>10-20 miles | Band 3<br>20-30 miles |
|---|---|---|---|
| Delivery density | 500 | 200 | 1 |
| # of routes | 261.8 | 314.2 | 5.3 |
| # deliveries/route | 600 | 600 | 296.5 |
| # of drones/truck | 8 | 7 | 5 |
| *PSAV* | 24.4% | 27.0% | 32.1% |
| *SPSM* | \$65.1 | \$33.5 | \$0.85 |
| % of area | **11.1%** | 33.3% | **55.6%** |
| % of deliveries | **45.2%** | 54.3% | **0.5%** |
| % of total savings | 38.3% | 59.2% | 2.5% |



# Divide a Region into Subregions

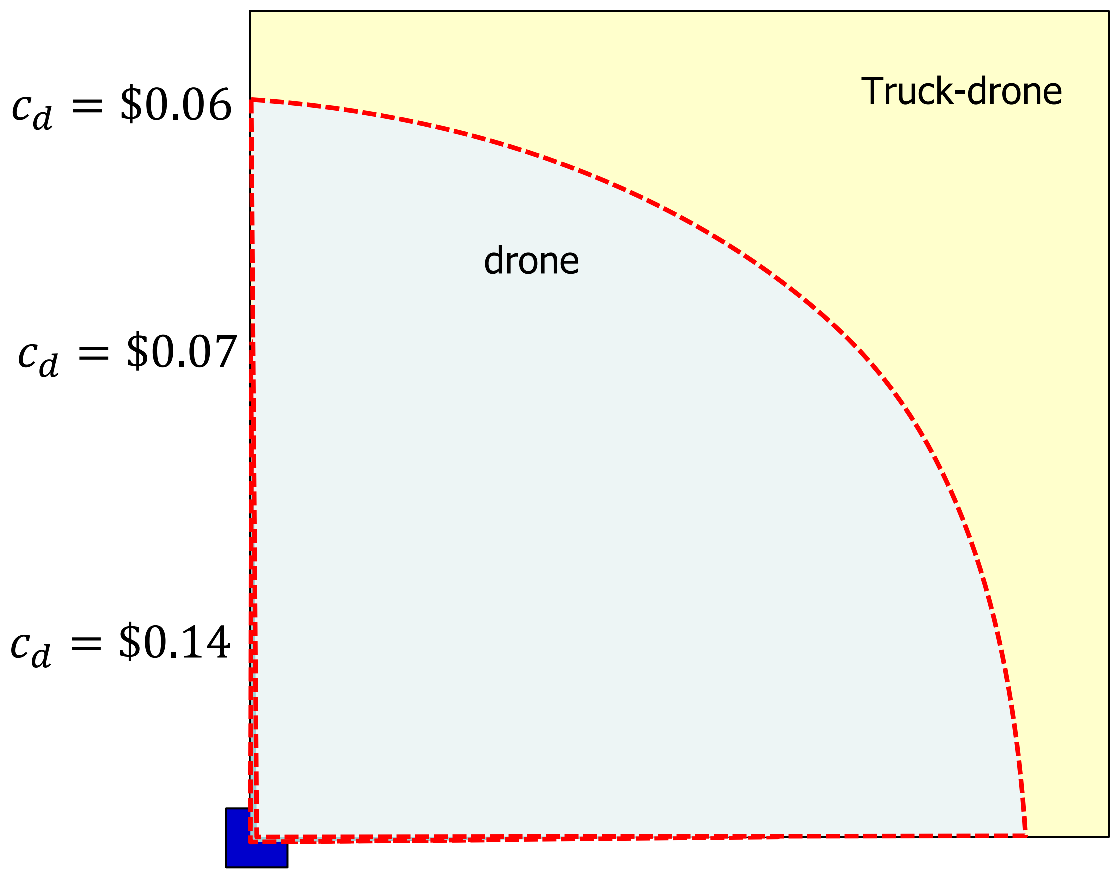
- Serve a region from a fixed depot with the best mix of (i) truck-only, (ii) drone-only or (iii) truck-drone delivery.
  - Depending on costs, any combination may be best…
- Common pattern is to use drones near the depot and use truck-drone routes farther from the depot.
  - Dividing line depends on drone operating and marginal stop costs.
- Compare costs of 3 options to identify which is best.



# Findings: Divide a region

- Dividing line can be found numerically; it is a nonlinear function of drone and truck operating costs.

$Truck\ cost = \$1.25/mile$

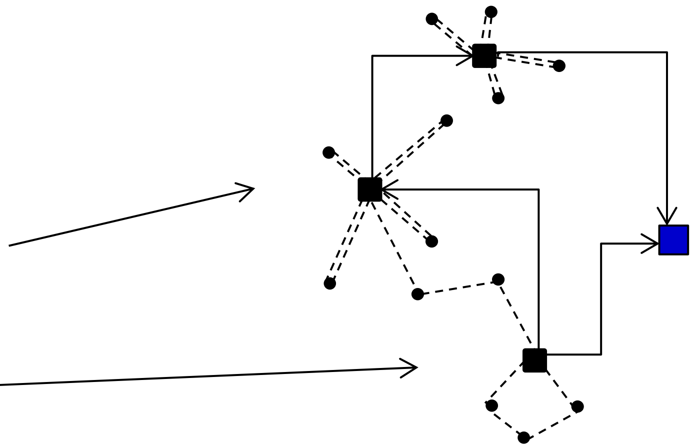


# Conclusions

- Hybrid truck-drone routes seem **attractive in many settings**, with largest benefits generally in denser regions (suburban areas)
  - For current proposed cost structures, drones would likely be heavily used in some areas.
- Allowing **multiple drones per truck** is very attractive.
- Drone use depends strongly on **drone marginal stop cost** and **drone operating cost.**
- **Multiple strategies** are best - with drone only close to the depot and truck-drone delivery farther away.

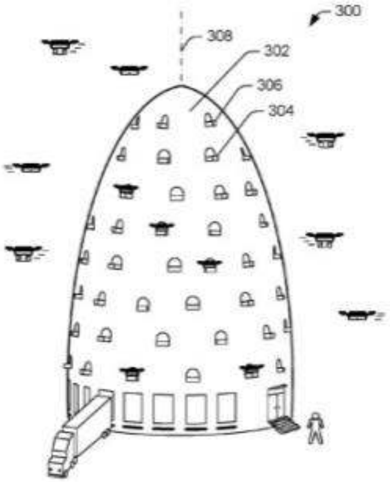
# Future Research

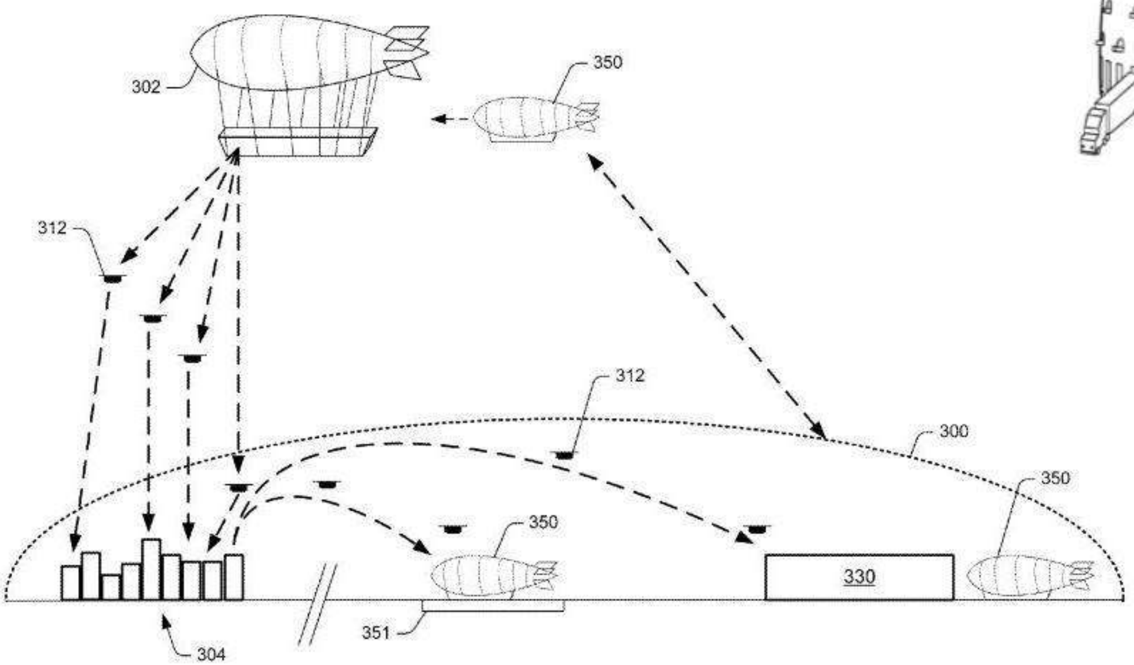
- Incorporate service requirements as time limits on delivery (30 minute, 1 hour, 2 hour, etc.).
- Assess cost-service trade-off.
- Model multiple drones per truck.
- Model multi-stop drone routes.
- Evaluate use of specific drone models.
- Case studies for rural, suburban, urban, regions.



# Part 3: More Future Research

- Blimp drone warehouses and Drone hives!?
- Location problems for drone delivery.
- Arc routing with drones.

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# Location Problems with Drones

- Locate depots, launch points, recovery points and recharge points (discrete and continuous)
- Objectives:
  - ➢ Minimize cost to serve demand (deliver to points, cover a network, cover an area)
  - ➢ Maximize the area served  from 1 or n depots
  - ➢ Minimize time to serve all demand
  - ➢ Minimize the Max time to serve demand

- Can formulate as covering problems….
  - Trucks and Drones: Two echelons
  - Location-Routing problems

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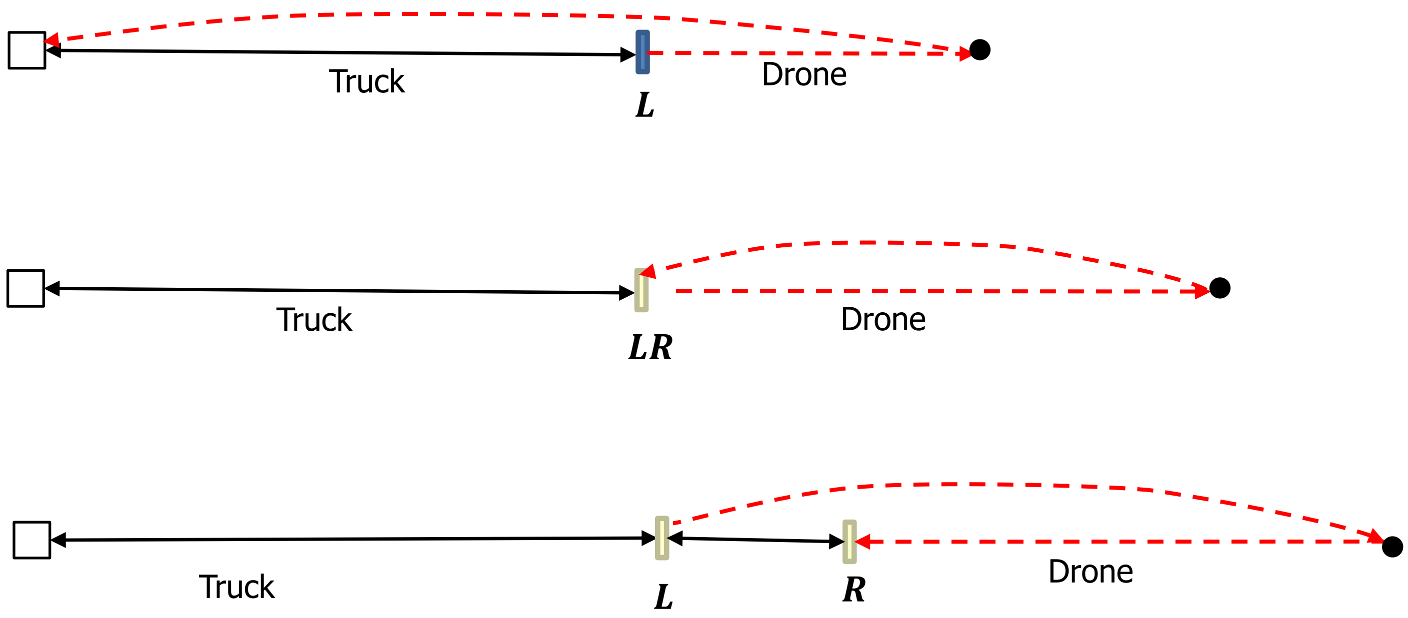
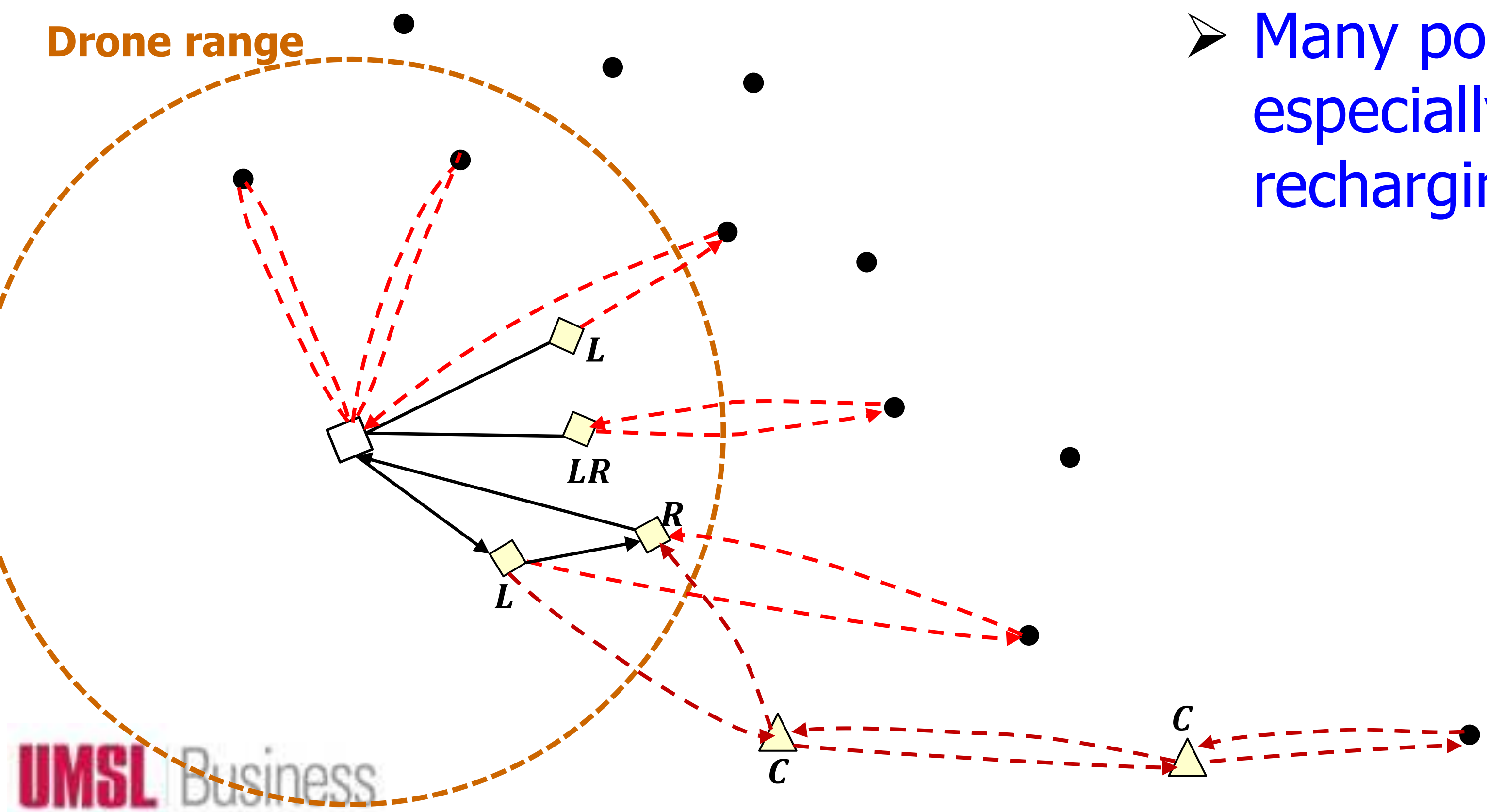
# Location Problems with Drones

- Locate launch ($\boldsymbol{L}$) and recovery ($\boldsymbol{R}$) points to extend the range
- Can also locate recharge points ($\boldsymbol{C}$)



# Location Problems with Drones

- $\boldsymbol{L}$ = launch point; $\boldsymbol{R}$ = recovery point
- $\boldsymbol{C}$ = recharge point



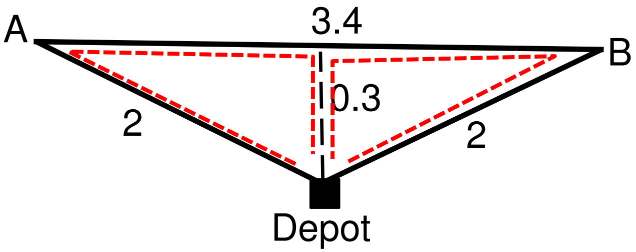

➢ Many possibilities, especially with recharging

# Arc Routing with Drones

- Drones service the arcs.
- Drones can follow the network – or not!
- Drone may start and end coverage of an arc at any point on the arc.
- Drones have a "capacity" limit on travel distance.
- Minimize the cost (or time) to service all required arcs.

**1. Drone Arc Routing Problem – DARP**

- Drones start and end at a given depot.

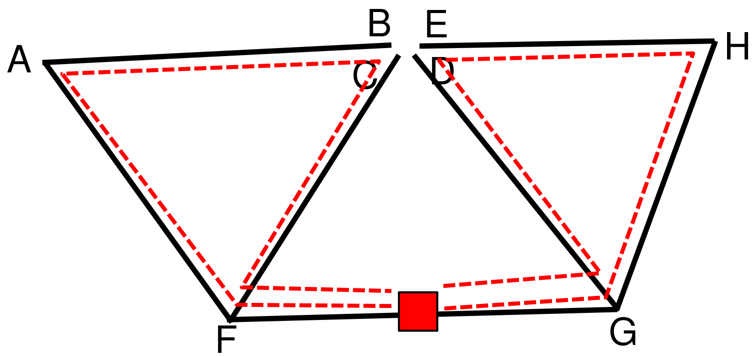



Drone has capacity 4

# Arc Routing with Drones

## 2. Drone Depot Location and Arc Routing Problem - DDLARP

- Locate one or more depots (drone bases) on the network. Drones start and end at a depot – or at the same depot.
- Minimize the # of depots, cost of depots, or total cost for depots and routes (or time for all routes)
- Drone travel distance ≤ B




Each arc length = 2
Drone and Truck have capacity 8

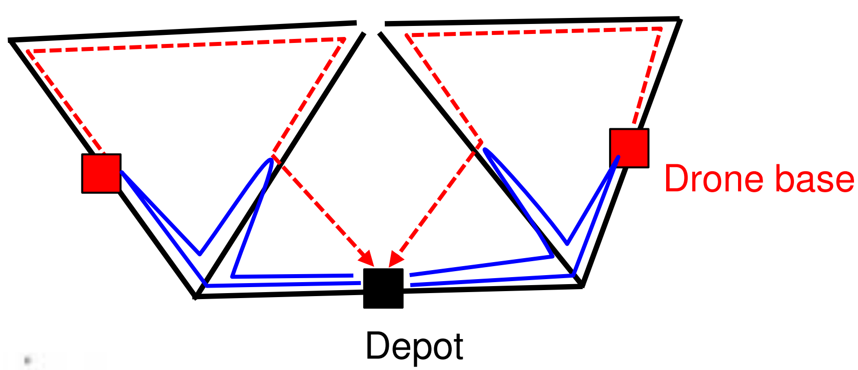
2 truck depots required at F and G
Truck length = 28

1 drone depot required
Drone length = 16

# Arc Routing with Drones

## 3. Drone Depot and Base Location and Arc Routing Problem - DDBLARP

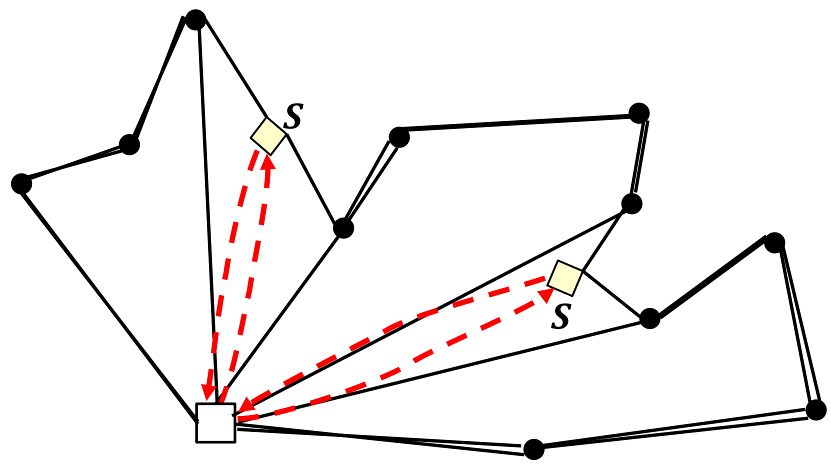
- Locate one or more depots and one or more drone bases (launch/recovery points) on the network.
- Truck drives from depot to a base to launch and/or recover drones.
- Drones start and end at a depot or a base.
- Minimize the # or cost of depots and bases, or total cost for depots, bases and routes.




Each arc length = 2
Drone has capacity 5
Truck has capacity 6

# Drones for Resupply of Delivery Vehicles

- Use large drones to resupply delivery vehicles (trucks, bikes) in the field with packages.
  - Vehicles do not need to return to the depot for resupply.
- Locate resupply points, $S$.
- Interacts with routing…



# In Summary…

- Many opportunities for good OR work on problems with drones…
- Costs and performance and not yet known (very well)…
- Combining drones and other vehicles adds richness and complexity…
- Assessing usefulness of drones requires better understanding near-optimal designs and near-optimal operations…


**Matternet Launching First Permanent Autonomous Drone Delivery Network In Switzerland**

September 25th, 2017 by James Ayre

The world's first permanent autonomous drone delivery network (as far as I know) will begin operating in Switzerland in October — transporting various diagnostics material, including blood tests, between various clinics, labs, and hospitals in the region.

# Thank you