



INSTITUTE FOR HOMELAND SECURITY

Truck-Drone Delivery Systems: Assessing Emerging Risks and Opportunities in Transportation Logistics

Juan Zhang, Ph.D. and Willow Yang, Ph.D.



**Sam Houston
State University**

TM

Truck-Drone Delivery Systems: Assessing Emerging Risks and Opportunities in Transportation Logistics

Juan Zhang, Ph.D.
College of Business
University of Wisconsin-Eau Claire
1zhangjua@uwec.edu

Willow Yang, Ph.D.
College of Business Administration
Sam Houston State University
willowyang@shsu.edu

Abstract

Truck-drone hybrid delivery systems are emerging as a promising solution to address the economic, operational, and environmental challenges of last-mile logistics. In this report, we provide a comprehensive analysis of their current state, strategic potential, and implementation roadmap. We begin by reviewing recent pilot programs and industrial models and highlighting strategic advantages such as faster delivery, reduced emissions, and improved cost efficiency. We then identify key operational, regulatory, and cybersecurity risks, from route optimization and fleet coordination to attack on drone sensors. Through a scenario-based modeling framework, we assess the cost and emissions performance of truck-only, drone-only, and truck-drone systems under various operational and regional conditions. Results show that truck-drone hybrids consistently outperform alternatives, with especially strong performance gains when trucks are retrofitted for multi-drone operations and fueled by low-emission sources. Finally, we outline a phased roadmap to bring truck-drone delivery from pilots to nationwide deployment. A skilled workforce for drone operations, maintenance, and cyber-physical security is essential for the successful implementation of this roadmap.

Keywords: truck-drone delivery, last-mile logistics, drone integration, autonomous aerial vehicles, economic and environmental assessment, workforce development

Contents

1.	Introduction.....	1
2.	Truck-Drone Delivery Systems: Current Landscape and Strategic Opportunities.....	2
2.1	The Emergence of Drone-based Delivery.....	2
2.2	Types of Drone-Assisted Delivery Systems	2
2.3	Strategic Business Models	5
2.4	Strategic Opportunities.....	6
3.	Emerging Risks and Challenges.....	7
3.1	Operational Challenges	8
3.2	Regulatory and Legal Constraints	9
3.3	Cybersecurity and Safety Threats	10
4.	Economic and Environmental Assessment	13
4.1	Modeling Approach and Baseline Scenario	13
4.2	Baseline Results: Truck-Drone Hybrid Model Offers Dual Advantage.....	14
4.3	Sensitivity Analysis: Understanding the Impact of Key Parameters	15
5.	Way Forward: Strategic Roadmap and Collaboration Models.....	21
5.1	Infrastructure and Airspace Readiness	21
5.2	Regulatory Alignment and Risk Management.....	22
5.3	Workforce Development	24
5.4	Way Forward: Strategic Roadmap and Collaboration Models.....	25
6.	Authors Biographies	28
7.	References	29
8.	Appendix A. Modeling Framework and Scenarios Data.....	37

1. Introduction

Last-mile logistics, which is the final stage of the delivery process that moves products from a local staging point to the customer's doorstep, is a critical component in the U.S. transportation network. It is one of the major factors that contribute to greenhouse gas emissions, and accounts for more than half of total transportation cost (Capgemini, 2019). The performance of last-mile deliveries can accelerate or hinder disaster relief efforts. It also determines whether rural communities receive time-sensitive goods and affects overall supply chain resilience.

Traditionally, retailers and logistics providers have been using techniques such as route optimization and dynamic parcel consolidation to improve the efficiency of last-mile deliveries. A promising advancement is logistic models which combine trucks and drones. It is a hybrid delivery model in which a ground vehicle serves as a mobile base station, carrying parcels, batteries, and launch equipment, while one or more drones are dispatched from the truck to complete nearby stops and then rendezvous with the truck down the route, thereby reducing total vehicle miles, time, and emissions for last-mile services. Industry pioneers such as Amazon Prime Air, UPS Flight Forward, and Wing (Alphabet's subsidiary) are currently conducting pilot programs to assess the viability of drone-assisted deliveries.

In this technical paper, we examine the opportunities and risks associated with the truck-drone delivery system. Specifically, we aim to:

1. Evaluate the current landscape and strategic advantages of truck-drone delivery systems, highlighting both the technological developments and specific use cases shaping this emerging field.
2. Assess the operational challenges, regulatory constraints imposed by entities such as the Federal Aviation Administration (FAA), and cybersecurity vulnerabilities that could impede safe and effective implementation of these emerging systems.
3. Conduct economic and environmental analysis to quantify potential impacts, analyzing the trade-offs between cost savings and emissions reductions.
4. Propose policy frameworks, collaborative models, and strategic roadmaps essential for bringing truck-drone delivery systems into routine service.

2. Truck-Drone Delivery Systems: Current Landscape and Strategic Opportunities

2.1 The Emergence of Drone-based Delivery

Since 2013, when Jeff Bezos announced that Amazon Prime members would get their packages delivered by drones within 30 minutes (Kelley, 2013), companies around the world have been actively exploring the use of drones (also known as unmanned aerial vehicles). These aircraft are capable of transporting small to medium payloads over moderate distances either autonomously or under remote oversight, thanks to advancements in automation, navigation systems and battery efficiency. They have apparent advantages in avoiding road traffic and improving delivery times. Academic studies and industry trials have shown that using drones not only lowers greenhouse gas emissions but also has the potential to reduce operating costs.

As of 2025, drone delivery is no longer just experimental. A real industry is emerging, supported by tens of billions of dollars investment worldwide (French, 2025). Companies like Wing, Zipline, Amazon, Walmart, and UPS have conducted tens of thousands of commercial deliveries in a range of settings from dense suburbs to remote rural areas.

2.2 Types of Drone-Assisted Delivery Systems

Drone-assisted delivery systems fall into two broad categories: drone-only and hybrid truck-drone delivery systems.

Drone-only Delivery Systems

In drone-only delivery systems, drones perform the entire delivery, launching from fixed infrastructure such as warehouses or fulfillment centers, stores, hospitals, or designated drone stations or nests. They take off from the base, fly autonomously or semi-autonomously to the delivery points, and deliver the package via landing, tether drop, or parachute. At the end they return to the same or a different base for their next delivery. This model currently dominates real-world deployments and commercial pilots. For instance, Wing, a subsidiary of Alphabet and representing one of the most mature drone delivery platforms, has conducted over 300,000 commercial deliveries worldwide since 2014. It has substantial activity in Logan, Australia, where daily volumes have peaked above 1,000 deliveries (McNabb, 2022). In the United States, Wing has operated in Christiansburg, Virginia, since 2019 under the FAA's Part 135 certification (Wing, 2019).

Zipline is another global leader for its pioneering work in long-range medical drone delivery. Launched in Rwanda in 2016, Zipline has now completed over 1.4

million deliveries and serves national healthcare systems in Rwanda and Ghana by delivering blood, vaccines, and pharmaceuticals to rural clinics. It has since begun adapting its model to the U.S., with a focus on precise home delivery and full end-to-end automation (Gavi, 2016; Loyalty Drones Team, 2024). Matternet specializes in short-range, high-frequency medical logistics. It partnered with UPS to launch the first FAA-certified drone airline, UPS Flight Forward, in 2019. Together, they began transporting medical lab samples at WakeMed Hospital in North Carolina. Matternet's quadcopters operate on fixed routes and land at designated drone stations. The company provides a controlled, hospital-to-hospital delivery model (U.S. Department of Transportation, 2019; UPS, 2019; Matternet, n.d.). DroneUp, a U.S. based drone logistics company, partnered with Walmart to conduct retail drone deliveries beginning in 2021. At its peak, DroneUp operated drone delivery hubs at 36 Walmart stores across seven states, making thousands of deliveries of household goods and groceries. Despite these accomplishments, Walmart scaled back the partnership in 2024 due to high costs per delivery and uncertain consumer demand (Walmart, 2021, 2023; Supply Chain Brain, 2024).

There are also other players that have achieved notable milestones. Manna Aero in Ireland has provided tens of thousands of grocery and food deliveries to suburban neighborhoods (PRNewswire, 2024). Antwork and JD.com in China take advantage of government support and advanced infrastructure to conduct commercial deliveries in urban centers (MN Shipping, n.d.). These international pilots often operate under more flexible regulatory frameworks, enabling faster scaling than what is typically possible in the United States.



Figure 1. Examples of real-world drone-only delivery pilots

Early implementations of drone delivery have shown a diverse and promising landscape. The concept has been technically proven, and the model is particularly beneficial in sectors such as healthcare. However, scaling these operations remains challenging given regulatory limitations and infrastructure gaps. It requires continued

investment and data sharing, and more importantly regulatory innovation to fully realize the benefits of drone delivery in the U.S.

Hybrid Truck-Drone Delivery Systems

In truck-drone delivery systems, a truck acts as a mobile depot that dispatches and retrieves drones in motion or at customer locations. While the truck drives along a route, drones are deployed to make nearby deliveries, often to locations that are out of the truck's direct path or would take extra time to reach. This hybrid model has two distinct advantages. First, it combines the range and payload capacity of trucks with the speed and navigational flexibility of drones, and second, unlike drone-only delivery, it can offer extend coverage without permanent infrastructure.

Academic research is most active in truck-drone models, with variations including the number of drones per truck, the primary role of trucks and drones (i.e., supply only, delivery only, or both), how rendezvous is coordinated (stationary or dynamic) and whether public transit (e.g., buses, trains) can be used as platforms. Despite theoretical advantages and interests, truck-drone systems remain largely in the prototype stage. One of the most notable tests is UPS's 2017 pilot in Florida, which was collaborated with Workhorse Group, Inc. During the test, a drone was deployed from the roof of a delivery truck. It demonstrated a reduction in vehicle miles and delivery time especially in low-density areas (UPS, 2017). Another concept example is Mercedes-Benz's "Vision Van," developed with Matternet. It proposed a fully electric delivery van equipped with rooftop drone bays and automated cargo management. While never deployed at scale, it is an example of the growing interest in purpose-built vehicles designed for hybrid aerial-ground delivery.



Figure 2. Mercedes-Benz Vision Van concept (source: <https://images.app.goo.gl/6fzjHrq2K3TJnRUb6>)

The lack of scaled pilots in truck-drone systems reflects barriers in operational complexity and regulations. Synchronizing drone and truck movements and managing drone storage and battery recharging on the truck all present significant challenges. There is also a lack of flexible regulations to support dynamic launch and recovery operations. Without a commercially available system for integrated launch-and-retrieval logistics, companies have largely focused on simpler drone-only systems.

2.3 Strategic Business Models

As the field evolves, we see three distinct business models begin to emerge:

Platform Service Providers

This category centers on specialized drone service providers. Companies such as Wing, Zipline, Matternet, Flytrex and DroneUp are part of this category. They provide end-to-end delivery services, not only offering routing and fleet management solutions but also developing drone hardware and software. Their platforms are often designed to be plug-and-play for retailers, healthcare providers, or logistics partners. A major advantage of this model is the development of proprietary infrastructure platforms that are highly automated and optimized for efficient deployment. For example, Wing's system features automated drone nests and advanced flight planning software, enabling operations with minimal human intervention. Zipline's new P2 delivery platform incorporates docking and charging hardware which can be mounted on building exteriors or installed as freestanding units. The platform, which resembles a streetlamp with an arm and a large disk (see Figure 3), allows drones to autonomously dock, offload empty loads, and collect new ones (Evans, 2024). According to Zipline CEO Rinaudo Clifton, installation requires effort comparable to setting up an electric vehicle charger (Zipline, n.d.).



Figure 3. Zipline Delivery Platform 2 (Source: Zipline.com)

Collaborative Models in Drone Delivery

Companies in this category include Walmart, UPS, and FedEx, which partner with drone service providers to incorporate drone delivery into their existing logistics networks. For example, Walmart has worked with DroneUp, Wing and Zipline to test deliveries of groceries and household goods from its retail outlets. As of 2025, Walmart has completed over 150,000 drone deliveries across more than 100 stores in five states including Texas, Florida, and Georgia (Walmart, 2025). UPS collaborated with Matternet for medical deliveries (UPS, 2019). In the meantime, FedEx is exploring a longer-range, middle-mile drone transport in collaboration with Elroy Air. The drone being tested is designed to carry up to 500 pounds over 300 miles and is intended for hub-for-hub freight. These examples demonstrate how drone delivery is being pursued through strategic partnerships that integrate drones into existing logistics ecosystems rather than as standalone solutions.

Full Internal Development

A third model is full internal development such as Amazon's Prime Air division. Amazon has taken a vertically integrated approach, building its own drone hardware, navigation systems and regulatory strategies. While there have been setbacks and progress has been slower than anticipated, the company conducted commercial deliveries in Lockeford, California and College Station, Texas in 2022. More recently Amazon has shifted focus toward improving automation to cut costs and expand service areas. Its latest MK30 drone is lighter, quieter, and capable of operating in diverse weather conditions (Greenawalt, 2024). The long-term goal of the company is to fully integrate drone delivery into its Prime fulfillment network, though it currently faces significant challenges in aligning regulatory requirements, automation readiness, and cost efficiency at scale.

2.4 Strategic Opportunities

Drone-assisted delivery is real and increasingly automated. Pilot projects have already demonstrated the reliability of the technology and that the model is valuable to customers. This is especially the case for short-range, time-sensitive trips such as prescriptions or critical medical supplies. Companies like Wing and Zipline have developed drone delivery systems that automate nearly every stage of the process from receiving an order to mapping the flight path and safely sharing the sky with other aircraft. Over time they will be able to run large-scale operations with minimal human oversight. These early successes point to multiple strategic opportunities:

- *Rapid response in healthcare and disaster relief.* Drones can move blood, vaccines or first-aid kits to remote clinics and disaster zones in minutes rather than hours,

buying precious time when roads are blocked or hospitals are far away.

- *Rural and hard-to-reach markets.* In sparsely populated areas, a drone's ability to leapfrog poor roads solves the "last 10 miles" problem that often makes rural delivery unprofitable.
- *Just-in-time retail.* Urban retailers can promise 30-minute drop-offs of high-margin items without keeping large inventories onsite. This frees up floor space and improves cash flow.
- *Lower carbon footprint.* For lightweight parcels, battery-powered drones can cut greenhouse-gas emissions compared with vans idling in traffic. This helps companies meet sustainability targets.
- *Supply-chain resilience.* By adding a fast, airborne leg to ground transport, firms gain a backup mode when highways are clogged, fuel is scarce, or labor is short.

When paired with trucks that function as mobile launch pads, drones extend the reach of existing fleets without duplicating their costs. Trucks manage bulk freight and heavier loads; drones take care of the urgent lightweight parcels that benefit most from their speed. This hybrid strategy captures the best of both worlds: ground efficiency and airborne agility. It opens the door to a scalable, resilient, and greener last-mile network.

3. Emerging Risks and Challenges

In this section, we examine the key challenges facing drone-based last-mile delivery systems, including operational complexities, regulatory and legal constraints, and cybersecurity and safety threats. Figure 4 below provides a visual summary of major issues.

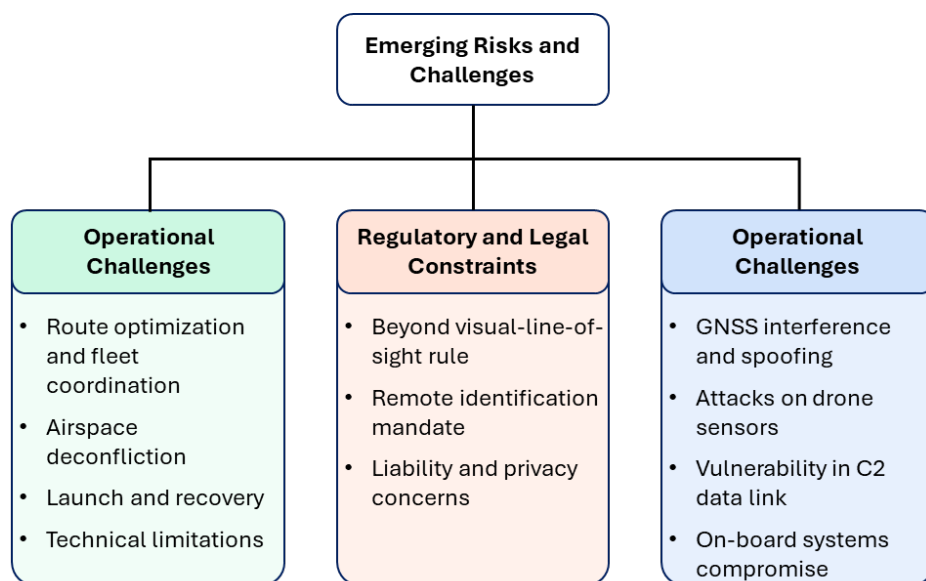


Figure 4. Summary of operational, regulatory, and cybersecurity challenges in truck-drone delivery systems

3.1 Operational Challenges

The integration of truck-drone delivery systems introduces a set of operational complexities that significantly differ from those encountered in conventional truck-only logistics. Below we discuss some of the major challenges.

Route optimization and fleet coordination

Because drones operate in three-dimensional space while their host trucks remain bound to road networks, scheduling algorithms must jointly determine when and where a drone should be launched, rendezvous, and retrieved, while also accounting for service-time windows and vehicle-capacity constraints. Existing heuristics designed for classic vehicle-routing problems often fail to capture these interdependent launch-and-recovery cycles, leading to sub-optimal utilization or infeasible routes (Dorling et al., 2016; Otto et al., 2018; Jahani et al., 2025). In addition, high sortie rates accelerate wear on rotors, batteries, and flight-control avionics. Integrating preventive maintenance windows and spare-parts logistics into routing and scheduling algorithms is essential to avoid cascading downtime and to ensure regulatory compliance (Sieb et al., 2023).

Airspace deconfliction

When multiple drones operate simultaneously, they compete for low-altitude airspace that is already shared with recreational unmanned aircraft system, emergency helicopters and in some regions, crewed general-aviation traffic. This requires real-time trajectory planning to avoid collisions. Currently, universal low-altitude traffic-management standards are lacking, forcing carriers to rely on proprietary sense-and-avoid capabilities. In addition, proprietary systems may not interoperate with neighboring fleets managed by other companies (Goodchild & Toy, 2018; Hu et al., 2024).

Launch and Recovery

Achieving safe vertical take-off and landing from a stationary or slow-moving truck demands coordination across mechanical design, sensing, and control algorithms. The truck must provide a stable launch platform (often a roof-mounted hatch or retractable pad) capable of compensating for minor roll and pitch, and the flight-control stack must evaluate launch windows in real time, accounting for truck speed, surrounding traffic, and local wind vectors. To mitigate mishaps, manufacturers incorporate redundant propulsion units, auto-abort routines, and fire-suppression shields around the pad. However, developing interoperable docking interfaces and a common set of rules, regulations and technical specifications remains an open research problem, as evidenced by the rapid increase in proprietary solutions now in field trials (Aretoulaki et

al., 2023). With this lack of standardization, any misalignment can result in aborted sorties, service delays, or damage to both the aircraft and the host vehicle (Murray & Chu, 2015; Karak & Abdelghany, 2019).

Technical limitations

Drones face a number of technical limitations affecting their operational range and reliability. For example, they are weather sensitive. Small, unmanned aircraft systems experience rapid performance degradation in rain, high winds, and extreme temperatures. Kim et al. (2021) demonstrate that head-winds as low as eight meters per second can reduce a quadcopter's effective range by more than 30%, necessitating either larger battery reserves or conservative flight-planning margins. In addition, most commercial drones currently certified for package delivery can lift between two and five kg, restricting their usefulness to lightweight, high-value, or time-sensitive items. Finally, battery endurance directly constrains flight time. Lithium-polymer cells suffer from temperature-dependent discharge rates and cycle ageing, resulting in range uncertainty and higher replacement costs. Despite advances in solid-state and hydrogen-fuel-cell technologies, their energy density remains an order of magnitude below that of liquid fuels. This again highlights the importance of hybrid truck-drone concepts where the truck covers the bulk of the distance (Lemardelé et al., 2021; Zhang et al., 2024).

3.2 Regulatory and Legal Constraints

Aerial operation in the United States (including drones) falls under FAA jurisdiction. The legal environment for truck-drone delivery system is rapidly evolving. Currently, Part 107 "Small Unmanned Aircraft Systems" under Title 14 of the Code of Federal Regulations requires a pilot must be able to see the drone at all times, known as visual-line-of-sight (VLOS). For a truck-drone system, this would severely limit the effective range of a drone dispatch from the truck. If the truck drives away, or the drone flies behind an obstruction (trees, buildings), VLOS is lost. This essentially makes autonomous, long-range drone deliveries from a moving truck impossible without waivers or new rules. The 2021 amendments permit routine flights over people and at night (FAA, 2021a), which improves service availability of drones. But, without a clear and broad beyond-visual-line-of-sight rule, fully autonomous, long-range, and efficient drone operation is not practical. The FAA's Aviation Rulemaking Committee has recommended a new Part 108 framework, but formal rulemaking is unlikely before 2026 (FAA BVLOS ARC, 2022).

On March 16, 2024, the Remote Identification mandate issued by the FAA officially took effect, which requires nearly all drones to broadcast or network-transmit their identification and location information during flight (FAA, 2021b). While the regulation is intended as a digital license plate for airspace safety, it significantly

complicates operations in large fleets of drones operating from trucks. In the meantime, companies must undergo a rigorous FAA approval process for aircraft design, known as Type Certification. UPS Flight Forward and Amazon are among the few operators that have obtained such certifications for their specific drone models. Both invested substantial capital and engineering hours (GAO, 2020). For smaller manufacturers, these are considerable barriers to overcome.

In addition, truck-drone delivery also faces legal uncertainties in liability and privacy. The existing regulations designed for traditional manned aviation and ground-based vehicles are often inadequate in addressing autonomous drone operations. For example, under traditional tort principles, operators can be held jointly liable for bodily injury or property damage resulting from drone mishaps; and the "immediate reaches" of airspace above private property is still a gray area (Evans, 2024). Several states (e.g., North Carolina) have begun to assert specific property rights for the airspace below 200 feet above ground level, which could expose drone operations from trucks to diverse and potentially costly litigation from landowners.

Similarly, there are privacy concerns due to the sensors and cameras on drones. The European Union General Data Protection Regulation is one of the world's strictest data privacy laws. It applies to any entity processing the personal data of individuals within the European Union, regardless of where the drone operator is located. In the U.S., despite the absence of a single comprehensive privacy law at the federal level, it is critical that operators proactively incorporate privacy protections into the fundamental design of hardware, software and operational protocols of drones to avoid potentially costly add-ons.

3.3 Cybersecurity and Safety Threats

Truck-drone logistics extend the traditional attack surface of unmanned aircraft. Advanced technologies such as mobile launch pads, edge computing devices, and multi-hop command-and-control (C2) links make truck-drone delivery possible, but they also introduce new points of vulnerability. Below we discuss some of the major threats facing unmanned aircraft operations, with a focus on how the same threats manifest in truck-drone systems.

Global navigation satellite system interference and spoofing

This is one of the most critical cyber-physical threats to autonomous flights. Global navigation satellite systems, or GNSS, is a collective term for Global Positioning Systems (GPS), Galileo, BeiDou, and GLONASS, which provide the precise timing and position fixes drone autopilots use to hold course and execute waypoints. Two attack modes can compromise this dependency. These are jamming, in which broadband

noise swamps the low-power satellite signal, and spoofing, in which a counterfeit waveform tricks the receiver into accepting false coordinates (Feng et al., 2020; Alrefaei et al., 2022; Sathaye et al., 2022; Nayfeh et al., 2023; Tlili et al., 2024). Once a drone is attacked, it may drift or descend.

In truck-drone logistics the stakes are higher than in static depots. A roadside jammer positioned along a delivery corridor can disrupt dozens of successive launches, while a mobile spoofer mounted on a passing vehicle could hijack drones in mid-route and direct them away from their retrieval trucks. Mitigation therefore requires layered defenses. Some of the techniques highlighted in the CISA (2023) GNSS guide and the NIST (2022) Positioning, Navigation, and Timing “profiles” include

- Pairing dual-frequency or RTK GNSS with inertial-visual sensor fusion
- Running real-time integrity checks cross-referencing barometric and optical-flow data
- Adopting authenticated navigation signals
- Invoking predefined contingency modes (e.g., return-to-truck or parachute deployment) if signal quality drops below a predefined threshold.

Attacks on drone sensors

Sensors play a critically important role in drone operations. They serve three core functions: navigation such as GNSS receivers, perception and collision avoidance such as cameras and light detection and ranging (LiDAR), and drone health monitoring such as battery gauges and current shunts. The very data streams that enable autonomous flight, however, also create new attack surfaces. Adversaries may jam or spoof range-finders with high-intensity LEDs or laser pulses, blind optical cameras with strobe lights, flood LiDAR returns with phantom points, inject false radar echoes, or apply adversarial patches so that neural-network detectors misclassify obstacles (Davidson et al., 2016; Cao et al., 2019; Fu et al., 2021; Cheng et al., 2022; Tu & Piramuthu, 2024; Wei et al., 2025). These attacks can trigger false positives that force emergency hovering or false negatives that lead to mid-air collisions. Risks amplify in truck-drone operations because every sortie must land on a moving pad amid roadway traffic. Fortunately, there are many countermeasures against drone sensor attacks, including

- Layered sensor diversity through radar-camera-LiDAR fusion.
- Adversarially trained perception models that learn to ignore crafted perturbations. Dynamic confidence scoring that throttles flight speed if any sensor’s data drift from baseline.
- Secure firmware/FPGA overlays that authenticate sensor data paths (Choi et al., 2018; Quinonez et al., 2020; Jeong et al., 2023; Nayfeh et al., 2023; Wei & Wang, 2023; Wei et al., 2024). Academic studies show that multi-modal fusion

can cut spoof-induced miss rates by an order of magnitude. These measures harden the sensor stack and help ensure that one compromised modality cannot cascade into a fleet-wide safety incident.

Vulnerability in C2 data link

Most delivery drones still transmit telemetry and receive commands over unlicensed 2.4 GHz or 5.8 GHz industrial-scientific-medical bands. This makes them susceptible to packet injection, session hijacking, and distributed denial-of-service floods. Attackers can replay a cached “return-to-home” packet or escalate privileges to assume full flight control. In fact, even low-cost, software-defined radios can saturate the narrowband link and force an automatic hover or crash. In truck-drone logistics the consequences can scale quickly: a single truck may cycle five to ten sorties per hour, so a jammed channel stalls the entire micro-fleet and triggers costly route deviations for the host vehicle. Naturally, any vehicle descending on traffic routes might also disrupt normal vehicle traffic.

Transitioning to 5G new radio and network slicing could potentially strengthen mutual authentication and differentiated quality-of-service. However, recent emulation studies show that misconfigured slices can leak bearer credentials or enable side-channel inference of flight paths (Bouzid et al., 2023). Moreover, 5G coverage along rural highways is patchy, forcing hand-offs back to Wi-Fi Direct, reopening the attack surface. Federal and international guidance therefore recommends a defense-in-depth posture:

- AES-256 or ChaCha20-Poly1305 link encryption
- FIPS-140-3 compliant secure-boot chains
- Hardware roots of trust for over-the-air update validation
- Frequency-hopping spread spectrum combined with adaptive power control to resist jamming (CISA, 2021; NIST, 2022).

Emerging best practice also deploys anomaly-based intrusion-detection sensors on the truck gateway to flag abnormal latency spikes or command rates and isolate compromised drones before cascade effects propagate through the fleet (Wang & Liu, 2022).

On-board systems compromise

On-board systems present an expansive attack surface involving both cyber risk and physical safety. Vulnerable firmware, unvetted third-party libraries, and poorly protected debug or UART ports allow adversaries to sideload malware or siphon telemetry. For example, a drone’s USB-C charging port could be exploited to push a kernel-level rootkit, disabling obstacle-avoidance sensors and inducing a controlled crash (Tian et

al., 2018). In truck-drone operations, a single truck often charges multiple drones through a shared power-data bus, so a compromised airframe can act as a “patient zero,” propagating malware laterally while the vehicle is in motion (Zemlianko & Kharchenko, 2023). Physical access risks also rise when trucks make fueling stops or during customer hand offs. These give attackers brief but repeatable windows to attach rogue devices or swap batteries.

Mitigation strategies include using secure-boot chains to verify signed firmware images at every power-cycle, deploying runtime attestation to periodically hash critical memory regions, and installing fire-suppression canisters rated for lithium-ion packs. Fleet operators are increasingly deploying containerized security agents on the truck gateway to scan inbound firmware updates and quarantine drones that exhibit abnormal power draw or sensor outages. The key is to prevent a single corrupted drone from cascading into a fleet-wide disruption.

In sum, cybersecurity and physical safety are inseparable in truck-drone operations. Effective defenses require a defense-in-depth architecture that combines secure hardware, resilient communications, continuous vulnerability assessment, and fail-safe flight-controls (Tlili et al., 2024). Without such measures, the economic and environmental benefits of truck-drone delivery could be undermined by a single well-executed cyber or safety incident. From a safety standpoint, any loss-of-link or loss-of-navigation event should trigger immediate flight-termination or parachute-recovery protocol. Meanwhile, sense-and-avoid failures due to sensor spoofing or machine-learning model drift could cause near-misses with crewed aircraft or collisions with obstacles. Employing adversarially trained perception models and redundant radar/optical fusion is an emerging best practice (Kong, 2021; Tu & Piramuthu, 2024; Wei et al., 2024).

4. Economic and Environmental Assessment

In this section, we evaluate the economic and environmental performance of truck-drone hybrid delivery in comparison to traditional truck-only delivery. To provide additional context, we also include drone-only delivery as it has attracted most industry deployments. This analysis provides decision makers with an evidence-based understanding of the net value of integrating drones into last-mile logistics under different operational, regional, and regulatory conditions.

4.1 Modeling Approach and Baseline Scenario

To assess the economic and environmental viability of truck-drone delivery systems, we developed a scenario-based modeling framework grounded in continuous approximation methods, a well-established approach in logistics planning (e.g.,

Daganzo, 1984; Campbell et al., 2017; Zhang et al., 2024). This framework estimates both the expected delivery cost and greenhouse gas (GHG) emissions performance of three distinct service configurations across a typical last-mile delivery region:

- **Truck-Only (TO):** Conventional last-mile (home) delivery where a truck visits a number of customers along a route, similar to standard operations by carriers such as UPS.
- **Truck-Drone (TD):** A truck carries multiple drones and launches them to serve nearby customers, while the truck also makes deliveries along its route.
- **Drone-Only (DO) Delivery:** A drone departs from the depot, serves one or more customers, returns to the depot, and repeats this for each delivery.

The analysis focuses on a typical suburban setting modeled after cities like Minneapolis, where residential deliveries are moderately dispersed, and neighborhoods are largely composed of standalone homes. In the baseline scenario, we assume a 10-mile radius service region, with a density of 25 deliveries per square mile. The vehicle fleet includes a Class 4 diesel-powered delivery truck capable of carrying up to 100 packages. In TD, each truck is paired with a battery-powered drone capable of carrying one package. Drone has a one-way flight range of 10 miles. Drone operations reflect full flight cycles, including takeoff/landing, ascent/descent, cruising, and hovering. This is essential to estimate the energy consumption of drone operations (Zhang et al., 2021). Cost and emissions estimates are based on national data for fuel prices, energy use, and the carbon intensity of the U.S. electricity grid. The baseline is designed to reflect what many retailers and logistics providers face today or may encounter in the near future. It serves two primary purposes:

- To provide a realistic benchmark for assessing current system performance, and
- To establish a foundation for scenario testing under different assumptions, such as more efficient drones, higher levels of automation, or cleaner energy inputs.

Technical details, model structures, and the data used in different scenarios are provided in the Appendix to support transparency and reproducibility.

4.2 Baseline Results: Truck-Drone Hybrid Model Offers Dual Advantage

The baseline analysis reveals that the truck-drone hybrid delivery system outperforms both conventional truck-only and drone-only delivery systems in terms of economic and environmental efficiency.

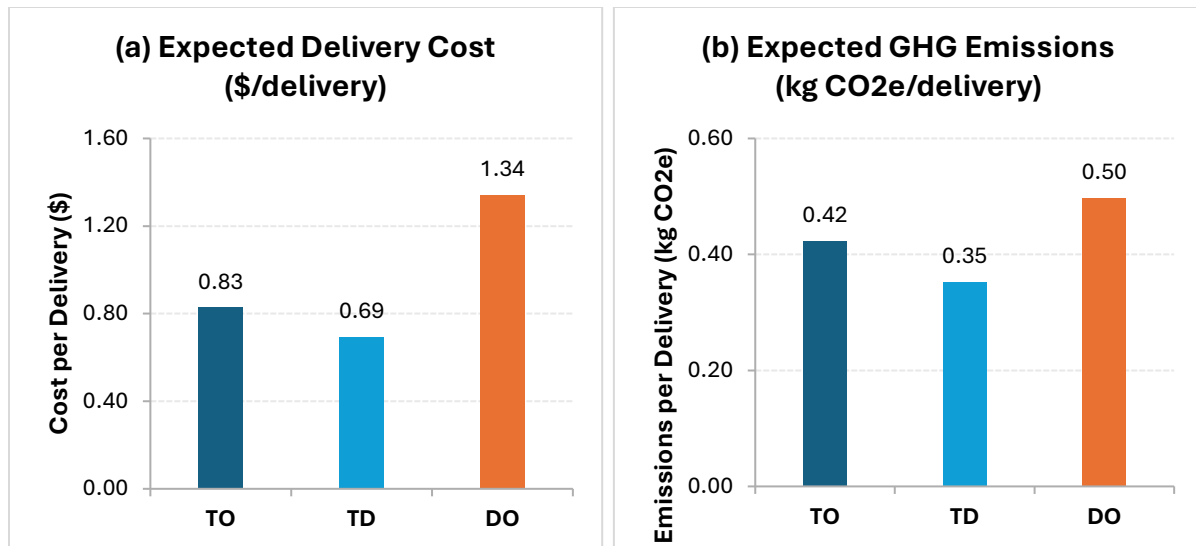


Figure 5. Baseline cost and emissions performance across three delivery models

As shown in Figure 5, the TD system achieves the lowest expected cost per delivery at \$0.69, significantly undercutting both the TO system (\$0.82) and the DO system (\$1.34). Importantly, this economic advantage is not gained at the expense of sustainability. The TD configuration also exhibits the lowest expected GHG emissions at 0.35 kg CO₂e per delivery, compared to 0.42 kg for TO and 0.42 kg for DO. These dual advantages of TD delivery come from combining the strengths of both vehicles: trucks provide efficient routing and the ability to carry large loads, while drones offer low-cost, low-emission delivery for lightweight and time-sensitive packages. By deploying drones from trucks to serve nearby customers, the hybrid system shortens delivery paths for both modes. In contrast, although drones are autonomous and battery-powered, potentially costing less per mile to operate and emitting fewer GHG emissions, the DO model suffers from minimal economies of scale due to its one-to-one delivery structure. Each drone must fly a roundtrip from the depot for every package, leading to longer cumulative travel distances, especially as delivery zones expand in size.

These results highlight the potential of hybrid truck-drone systems to lower both last-mile delivery costs and emissions at the same time. For policymakers and logistics providers, this makes a strong case for backing the rollout of such combined delivery models.

4.3 Sensitivity Analysis: Understanding the Impact of Key Parameters

In this section, we examine how cost and emissions performance shifts when key parameters are adjusted. To structure the analysis, we categorize the key parameters into three groups:

- **Drone-related parameters** include drone non-fuel operating cost, drone payload capacity, and drone energy consumption. These parameters are significantly influenced by drone design, operational practices, and the regulatory environment governing autonomy and airspace use.
- **Truck-related parameters** include the number of drones a truck can carry, truck payload capacity, and truck fuel type. These parameters are mainly influenced by the capabilities of trucks.
- **Region-related parameters** include delivery density, service region size, and carbon intensity of local electricity grid. These factors vary considerably across geographic regions.

4.3.1. Drone Parameter Experiment Results

Our analysis shows the truck-drone hybrid model maintains stable cost and emissions performance across a wide range of drone-related parameters, while drone-only model is highly sensitive to changes in drone cost structure, payload capacity, and energy efficiency. As shown in Figures 6a and 6b, variations in drone operating cost have no effect on emissions and only modest impact on TD costs. At 5x the baseline cost, TD's delivery cost increases by just 10%, yet remains cheaper than TD. At 0.2x the baseline, TD's cost drops marginally. By contrast, DO costs surge past \$6 per delivery at 5x scenario but fall to just over half the cost of TD at the 2x scenario. This highlights a narrow window in which DO is cost-competitive.

Drone payload capacity has a notable impact. For DO, doubling the payload halves both cost and emissions, closing the gap with TD. While TD sees more modest gains, its performance remains consistently strong, reinforcing its robustness even with low-payload drones. Drone energy consumption is a critical emissions driver, particularly for DO. At 5x baseline energy use, DO emissions spike fivefold, while TD remains relatively stable. DO costs also rise 38% under high energy use but improve slightly (8%) at lower consumption. Again, TD's performance varies only marginally in either direction.

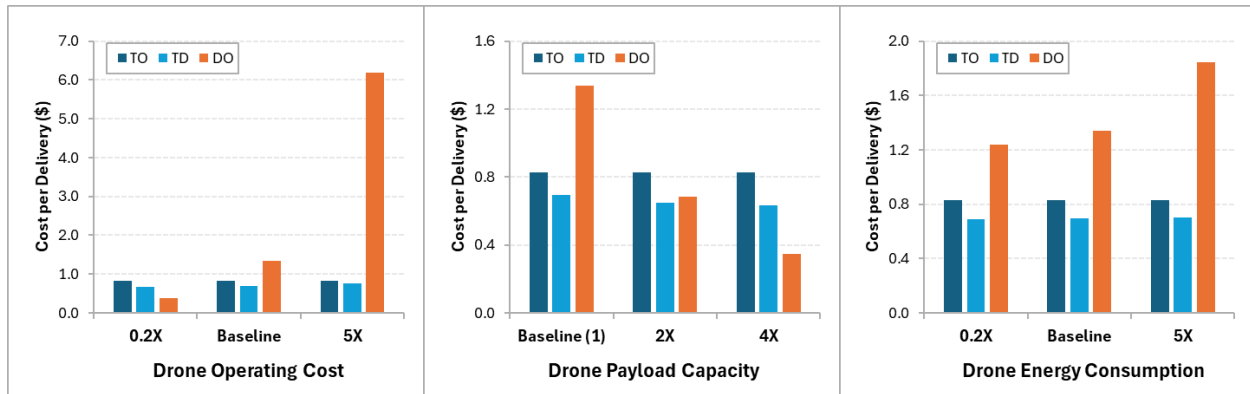


Figure 6a. Impact of drone-related factors on cost performance

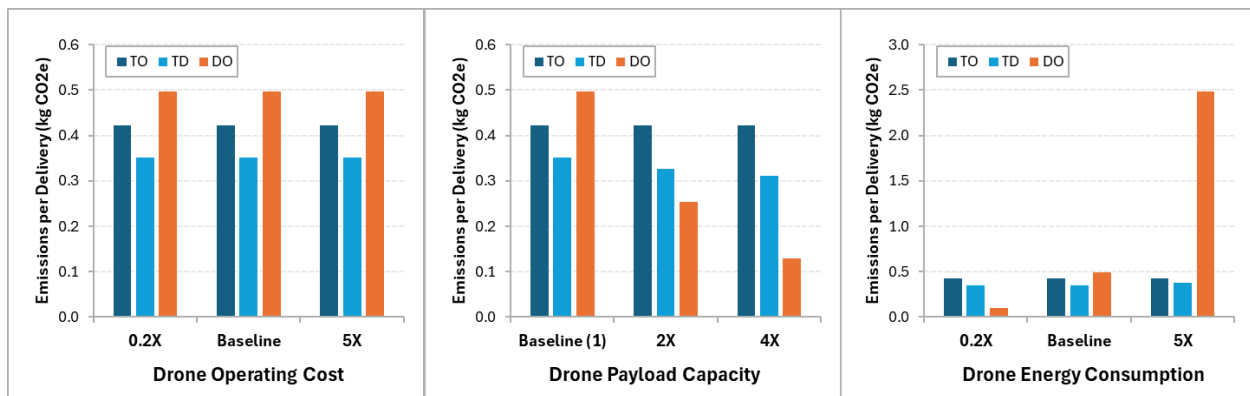


Figure 6b. Impact of drone-related factors on emissions performance

These findings underscore the resilience and flexibility of truck-drone hybrid systems, especially for near-term deployment under current technological and regulatory constraints. Unlocking the full potential of drone-only systems, however, will require (a) investment in automation and labor-efficient operations, (b) incentives or support for high-payload and energy-efficient drone designs, and (c) streamlined regulation to enable scalable drone operations

4.3.2. Truck Parameter Experiment Results

Truck-related parameters, specifically drone count per truck, truck payload capacity, and fuel type, have a significant impact on truck-drone system performance. As shown in Figure 7a and 7b, increasing the number of drones per truck from 1x to 2x (or 4x) reduces the expected delivery cost and emissions of TD by 8% (or 16%) and 9% (or 17%), respectively. Expanding further to 6x yields diminishing returns, with only incremental additional savings. This suggests that a lower number of drones per truck may balance operational complexity and efficiency.

Truck payload capacity is a major efficiency lever for TO and TD. At 2x baseline truck payload, delivery cost and emissions per trip of TD are both reduced by approximately 22%. In contrast, cutting payload capacity in half leads to a 44% increase in both cost and emissions. TO follows the same direction but with smaller magnitudes of -18% to +37%, indicating TD's advantage over TO widening with larger payloads. In real-world operations, payload capacity is often constrained not only by vehicle size but also by operating hours. Drones enable trucks to serve more stops per route, effectively increasing payload utilization without extending delivery times.

Switching truck fuel from diesel to electric or compressed natural gas significantly reduces emissions for both TD and TO by 20-24% and 20-26%, respectively, with minimal impact on delivery costs. Again, the TD model retains its advantage across all fuel types.

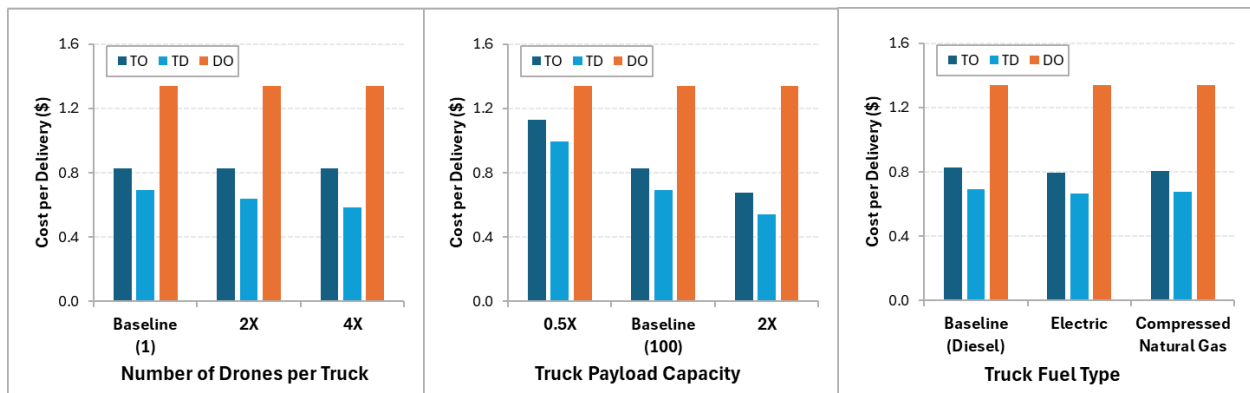


Figure 7a. Impact of truck-related factors on cost performance

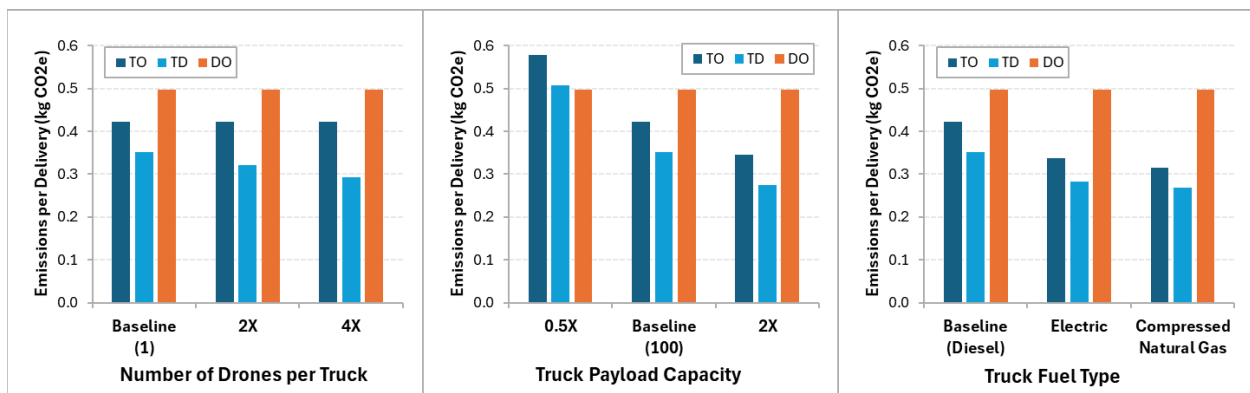


Figure 7b. Impact of truck-related factors on emissions performance

In sum, the hybrid truck-drone system offers significant potential for performance improvements through truck-level enhancements. Increasing the number of drones per truck, boosting truck payload capacity, and shifting to alternative-fuel vehicles all

strengthen the case for adopting the hybrid model. For government agencies and fleet operators, these findings reinforce the value of integrating drones with broader fleet modernization efforts to achieve both cost savings and large-scale decarbonization.

4.3.3. Region Parameter Experiment Results

Region-specific factors such as delivery density, service area size, and carbon intensity of electricity affect the cost and emissions performance of last-mile delivery systems in distinct and non-uniform ways. These variables are critical for tailoring deployment strategies to local conditions. As shown in Figure 8a and 8b, delivery density has a major impact on truck-based systems (TO and TD), but it does not affect DO performance. At low delivery density (0.04x baseline), TO and TD systems experience a sharp increase in cost and emissions due to longer travel distances and reduced routing efficiency. Under these conditions, DO becomes the lowest-cost option. However, as density increases to 25x baseline (e.g., urban areas), both TO and TD gain substantial efficiency and restore their advantage, achieving cost and emissions reductions exceeding 45%.

Service area size affects all three systems but has the greatest impact on DO. In compact delivery zones (2-mile radius) such as dense city centers or walkable neighborhoods, DO is the most cost- and emission-efficient option. Even at 5 miles, DO maintains a lower emissions profile and reaches cost parity with TO. However, as the service area expands to 10 miles, DO's one-to-one roundtrip limitation results in steep performance losses, while TD and TO become relatively more efficient, showing their suitability for larger geographic areas.

Electricity carbon intensity does not impact cost but significantly affects emissions for electric-powered systems like DO. TD emissions remain largely unchanged in our model, assuming a diesel-powered truck. In low-carbon regions like California, DO emissions are significantly lower. In high-carbon states, DO's environmental performance deteriorates, emphasizing that DO systems are only as green as the grid they rely on.

Local geography and energy context should be core considerations when evaluating or regulating last-mile delivery systems. While the DO system may be attractive in dense, compact, or highly walkable urban areas, its performance deteriorates in serving customers located farther from the depot. Interestingly, DO systems also appear competitive in low-density rural areas, not because they perform better but because truck-based systems perform much worse under such conditions. In contrast, the truck-drone hybrid model shows greater resilience and adaptability across a broader range of conditions.

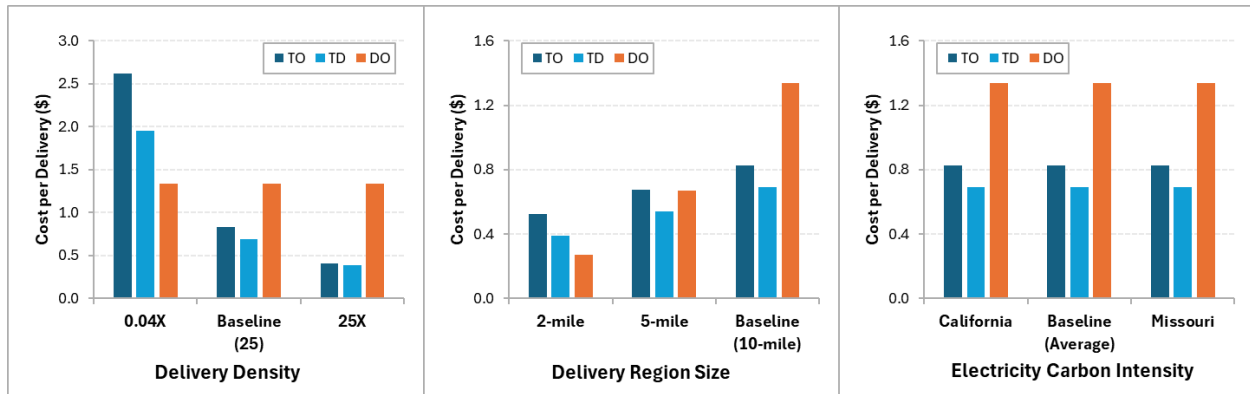


Figure 8a. Impact of region-related factors on cost performance

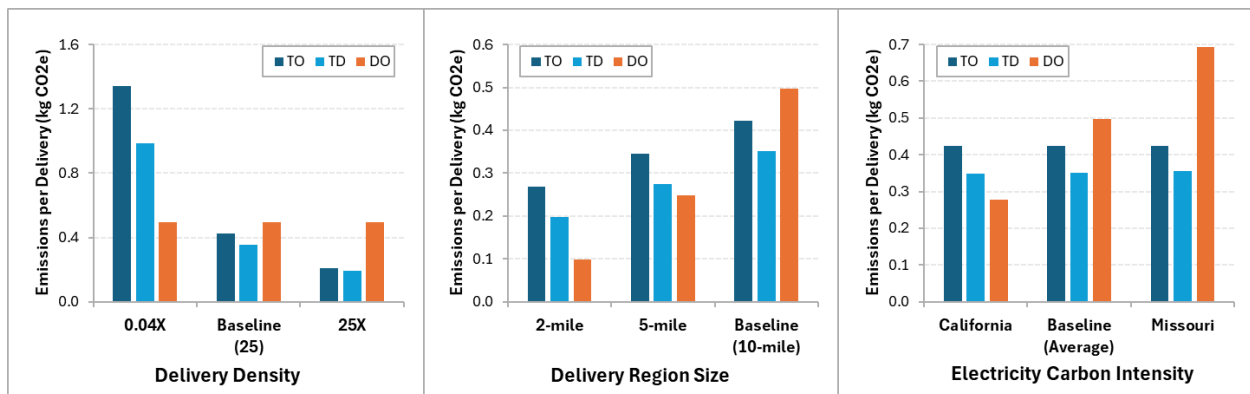


Figure 8b. Impact of region-related factors on emissions performance

In summary, truck-drone hybrid systems stand out as the most resilient and adaptable delivery strategy, consistently outperforming truck-only and drone-only systems across a range of operational, regulatory, and regional scenarios. While DO systems may be viable in select contexts, such as compact urban areas or sparsely populated regions with clean electricity, their performance is highly sensitive to drone design, energy consumption, automation levels, and the regulatory environment. By contrast, TD systems demonstrate stable and scalable performance across diverse conditions, making them a strong candidate for broader deployment. Importantly, its efficiency and competitiveness can be further enhanced through targeted investments in truck configuration, including the number of drones a truck can carry (which may require regulation support), payload capacity, and transition to low-emission fuels. These findings highlight the TD model as a practical and policy-aligned pathway for modernizing last-mile logistics in both urban and rural environments.

5. Way Forward: Strategic Roadmap and Collaboration Models

5.1 Infrastructure and Airspace Readiness

Delivering packages from moving trucks with autonomous drones demands an integrated ground-to-air ecosystem that is far more complex than the static hubs used by traditional drone depots. Two mutually dependent pillars, physical infrastructure and managed low-altitude airspace, must be ready if truck-drone logistics is to scale safely and economically.

Ground infrastructure

- **Launch-and-recovery hardware.** Trucks require roof-mounted or telescoping vertical take-off and landing pads engineered for roll-and-pitch compensation, automated hatch covers, and impact-absorbing skids. Current prototypes support one or two drone “parking bays.” A commercial fleet will need modular pads rated for at least 8 to 10 sorties per hour, hot-swap battery drawers, and automated health-status handshaking with the truck telematics bus (Mesgarpour et al., 2013; Battiato et al., 2017; Ghommam & Saad, 2017; Junaid et al., 2017; Si et al., 2024; Sohail et al., 2025).
- **Power and charging networks.** High-cycle lithium-ion or Li-metal batteries must be recharged or swapped multiple times per route. Operators can choose on-board high-power DC chargers (fed by the truck’s alternator or auxiliary battery) or curbside micro-depots that serve several trucks in a region. Either model calls for UL-listed charging hardware, Class D fire-suppression systems, and over-temperature cut-outs (Herath et al., 2017; Voznesenskii, 2021; Hert et al., 2023).
- **Edge-computing gateways.** A hardened gateway, such as an ARM or x86 single-board computer, is mounted inside the truck for processing data locally and making rapid decisions without constant reliance on a central cloud, especially when there are connectivity challenges on the road. The gateway can be used to coordinate drone traffic management messages, GNSS integrity checks and real-time flight-path optimization. To support heterogeneous fleets, the gateway should make its APIs available and run containerized security agents capable of deep-packet inspection without disrupting 5G or Wi-Fi direct hand-offs (Casalicchio & Iannucci, 2020; Gao et al., 2020; Ayass et al., 2022; Janßen et al., 2023; Głąbowski et al., 2024; Isik et al., 2024; Singh et al., 2024; Meng et al., 2025).
- **Maintenance and depot network.** In a highly efficient commercial delivery service, drone sortie rates may exceed 50 cycles per day per drone. Preventive maintenance depots equipped with rotor-balancing rigs, battery impedance testers, and firmware-signing stations need to be in place, spaced roughly every 100 – 150 miles along

primary routes, so a truck would never be far from a necessary service point. Digital twins of each drone can feed predictive maintenance analytics for scheduling truck routes around required inspections (Petriloti et al., 2018; Poikonen & Campbell, 2021; Mohsan et al., 2023; Xing & Johnson, 2023).

Airspace readiness

- Corridor design and geofencing. To keep drones from crossing paths with airplanes or hobby flyers, most plans call for low-altitude “drone lanes” that run 60–120 meters above the ground alongside major highways. Digital fences around these lanes must update in real time to reflect new flight advisories, emergency-use airspace, or moving hazards like medical helicopters (Muna et al., 2021; Kim & Atkins, 2022; Thomas & Sarhadi, 2024).
- Unmanned-traffic coordination. Recent FAA and NASA trials show that cloud services can prevent conflicts by taking each drone’s planned route, checking it against others, and issuing safe detours in seconds. Truck-drone operators will need either their own link into this system or a secure connection to a third-party provider so they can file flight plans, learn about airspace limits, and share their live position data (NASA, 2018; Al-Nabhan et al., 2025; FAA, n.d.).
- Detect-and-avoid capability. Industry standards say drones must be able to spot unexpected aircraft 400–600 meters away. Because many drones gather near a truck at take-off and landing, they should also broadcast simple “I am here” signals to one another using light versions of ADS-B or Wi-Fi beacons to back up their onboard cameras and radar (Ruseno et al., 2022; Attin & Bonnedahl, 2024; Yue, 2024).
- Reliable positioning signals. Accurate location and timing data are essential. Drones should combine two-frequency GPS with readings from barometric sensors, onboard cameras, and even the truck’s wheel sensors so they can keep their position within a few centimeters, even if GPS signals are jammed or faked (Varshosaz et al., 2019; Khan et al., 2021; UAV Navigation, 2021).

5.2 Regulatory Alignment and Risk Management

Real-world deployment of truck-drone delivery cannot advance beyond limited pilots until regulation, standards, and enterprise risk-management practices converge on a common, predictable framework. In this subsection, we outline the critical alignment tasks at the federal and state levels and discuss the complementary risk-management mechanisms that operators can adopt while formal rulemaking is underway.

Align federal rule-making with industry timelines

The drone industry and federal regulators need to move in step so that truck-launched delivery can grow beyond small pilots. A top priority is a clear rule that lets drones fly safely beyond the driver's line of sight without relying on one-off waivers. The FAA already has a risk-based outline ranging from "shielded" low-risk routes to higher-risk over-people flights, but it needs to convert that outline into a full rule and evaluate operators by measurable safety performance such as how well their drones can sense and avoid other aircraft rather than by rigid hardware checklists. Companies can speed this process by sharing solid data from corridor trials and show their detect-and-avoid systems and Remote-ID signals can work reliably (Bagnall et al., 2024; Magdolna, 2024; The Rock Robotic Team, 2024). At the same time the approval path for new drone designs needs to become quicker and less expensive, especially for smaller manufacturers. One way is to let proven companies self-certify minor design tweaks once the FAA has approved the baseline model so safety fixes and battery upgrades can reach the field sooner (Shumaker, Loop & Kendrick, LLP, 2018; Changes to Type Certificates, 2025; McNabb, 2025). Finally, regulators should spell out that the rooftop launch pad on a truck is simply a portable heliport subject to basic fire-safety and load limits, rather than treating each pad as a one-off exception (FAA, 1994; FAA, 2014; HeliExperts International, n.d.). Clear, flexible rules in these three areas will allow the technology and the market to mature together without compromising safety.

Aligning federal and local rules

Consistent federal and local regulations are key to successful truck-drone delivery. A national model law could establish a standardized airspace floor, perhaps 200 feet above ground level. Below this designated height, landowners would retain their property rights, while above it, commercial drone operations would be permitted. This resolves inconsistent trespass disputes (Dukowitz, 2025). States could also adopt a unified 'UAS Data Transparency' standard so that privacy notifications and data retention policies are the same from county to county. Lastly, permits for truck-mounted drone launch pads should be standardized through a common template similar to established ride-share pickup zones (City of Houston, 2019), which will make it far easier for carriers to plan routes that span multiple cities.

Enterprise risk-management frameworks

Truck-drone operators need a structured way to spot problems before they run into accidents or data breaches. From a flight safety perspective, companies should run a "what-if" analysis for every route, looking at who is on the ground, what other aircraft are nearby and how fast a drone could glide down in an emergency. Then, using those findings to add parachutes, geo-fences or extra sensors as needed. On the cyber side, they can follow the federal playbook, which lists simple steps for protecting GPS

signals, control links and onboard software from secure boot-up checks to regular intrusion scans. In terms of quality, companies can leverage aircraft industry practices by keeping a living record of each drone's parts, suppliers, and design tweaks so any defect is traced and fixed quickly. By tying incident reports, cyber logs, and maintenance records into one integrated risk-management system, operators could not only satisfy regulators more easily but also build trust with local communities and investors who want proof that the new service is both safe and reliable.

5.3 Workforce Development

Operating a hybrid truck-drone fleet demands cross-disciplinary skillsets across aviation, logistics, and information technology. Below we outline some emerging professions, along with their required core competencies and primary talent sources.

Roles	Core Competencies	Primary Talent Sources
Drone operations specialist	BVLOS remote-pilot certificate, real-time risk assessment, drone traffic management interface skills	Commercial drone pilots, traditional aviation professionals, military unmanned aircraft system operators and technicians
Truck-pad technician	Mechanical and electrical troubleshooting of launch-and-recovery systems, battery handling, lithium fire-suppression procedures	Diesel mechanics, aviation ground handlers
Fleet cyber-operator	Network segmentation, GNSS-spoofing detection, secure-boot and over-the-air update management	Security operations center analysts, avionics cybersecurity engineers
Data & AI engineer (logistics)	Multi-sensor fusion pipelines, adversarial robustness testing, reinforcement-learning route optimization	Robotics or machine-learning graduates
Regulatory compliance lead	Safety management system documentation, ISO/AS9100 audits, incident investigation, privacy-by-design	Safety managers, aviation quality-assurance staff

New education and training models are on the rise to support the unique demands of truck-drone logistics. One option is four- to eight-week long certificate programs. These courses could help truck mechanics and technicians quickly transition into drone-related roles such as launching, guiding, landing and servicing drones on a moving truck. Another approach is structured apprenticeships combining paid, hands-on work with classroom instructions to give entry-level workers both hands-on experience and a consistent safety mindset. Advanced simulator training is also a valuable option to

allow remote pilots to practice complex scenarios like truck-based drone launches beyond visual line of sight. Finally, because drones rely on both software and hardware, employees may need to learn cybersecurity alongside mechanical upkeep. Cross-training courses should follow national security guidelines and teach tasks such as checking secure start-up software and testing GPS signals right next to routine maintenance jobs.

Truck-drone systems will generate jobs across both urban distribution centers and rural smart corridors. However, without intentional investment, these new opportunities could widen existing workforce gaps. To address this, rural colleges near drone corridors may be equipped with unmanned aircraft system training labs, helping local residents gain access to technician and operator roles. Veterans also represent a strong talent pool; many already have drone experience from military service. Creating a fast-track pathway to recognize their flight hours and issue civilian credentials could ease their transition into the industry. In the long run automation may gradually reduce the need for long-haul truck drivers. The public, private and academic sectors could offer scholarships to retrain these workers in drone or cyber-maintenance roles. This can help logistics companies retain experienced personnel while transitioning toward more automated operations.

5.4 Way Forward: Strategic Roadmap and Collaboration Models

Bringing truck-drone delivery from pilot corridors to nationwide service requires tightly sequenced milestones and an explicit framework for public-private-academic collaboration. The picture below describes the strategic roadmap of truck-drone logistics.

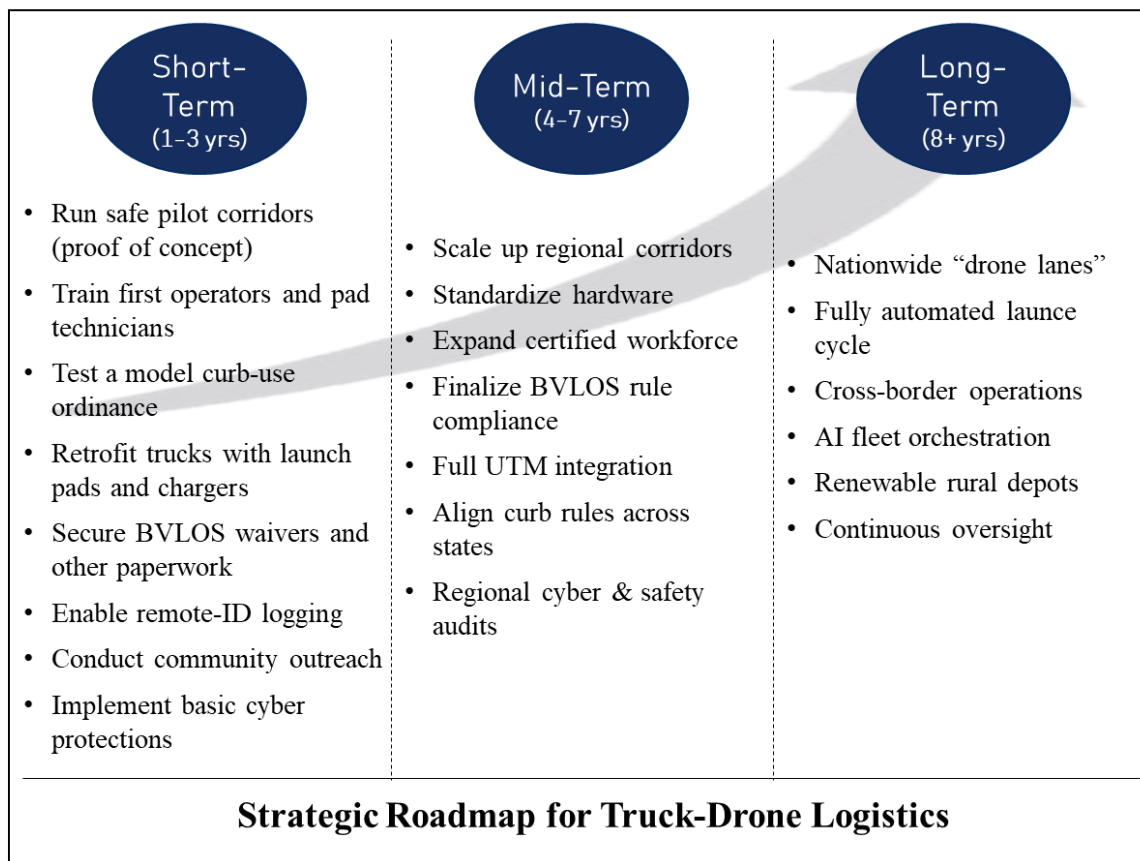


Figure 9. Strategic roadmap for truck-drone logistics

In the short term, the goal is to prove that truck-launched drones can work safely and smoothly. First, companies need to run small pilot routes and gather hard data on performance and safety. They will train the first wave of remote pilots and pad technicians so each truck has qualified staff. At the same time, local governments will test a standard curb-use rule that lets trucks stop and launch without clogging traffic. Trucks in the pilot fleet will be fitted with simple launch pads and battery chargers, and operators will complete all FAA paperwork, including waivers for flying beyond the driver’s line of sight. Every drone will broadcast a Remote-ID signal and store flight logs, while community-outreach teams explain the project and listen to residents’ concerns. Finally, basic cybersecurity steps such as encrypted control links and secure boot-up checks need to be in place to keep hackers out. Together these actions lay the foundation for scaling up in the years that follow.

In the mid-term, the focus shifts from small pilots to regional scale-up. Pilot routes will stretch across several states to form “smart corridors” with shared charging depots along major highways. Launch pads and battery packs will follow a common industry standard so any truck can work with any drone. The workforce may grow from a

few hundred specialists to several thousand, all holding a national certificate that covers both flying beyond line of sight and pad safety. By this stage, the FAA's new long-range drone rule should be in place, allowing operators to switch from temporary waivers to permanent licenses. Every flight plan will flow through a cloud traffic-management system that automatically reroutes drones around busy airspace. Meanwhile, at least ten states may have adopted the same curb-use and privacy rules, making it much easier to run multi-city routes. Independent auditors will check each operator's cybersecurity and safety data once a year, ensuring that good practices learned in the pilot phase scale up with the fleet.

In the long term, truck-drone delivery is expected to run almost automatically and nationwide. A web of low-altitude "drone lanes" will stretch across the country, coordinated in real time by a national traffic-management network that keeps drones clear of other aircraft and temporary no-fly areas. Trucks will carry fully automated launch pads and robot arms will swap batteries and send drones off. Behind the scenes, artificial intelligence software will assign drones to trucks on the fly, choosing the most energy-efficient match for each parcel and route. Charging depots will mostly run on solar, wind, or other clean power to reduce cost and keep carbon footprints low. Workforce programs that started earlier will pay off with former long-haul drivers and rural residents filling skilled drone-support jobs at rates that match national averages. Live flight data will stream to a federal safety portal, giving regulators continuous oversight and allowing rules to be updated quickly when new risks appear so the system is kept safe even as it scales.

Across three time frames, there are three major themes. First, steady investment in R&D – particularly for higher-density batteries, smarter payload handling, and AI-powered routing – will keep performance and safety improving year after year. Second, for successful scaling, robust public-private-academic collaborations are crucial. For example, universities advance scientific understanding, industry turns ideas into practical tools, and government streamlines the regulatory environment. Lastly, every phase of rollout shall be guided by a data-driven risk management framework, so safety lessons learned in small pilots are captured, shared and built into national rules.

6. Authors Biographies

Dr. Juan Zhang is an Assistant Professor for Supply Chain Management at the University of Wisconsin -Eau Claire (UWEC). She earned her Ph.D. in Business Administration emphasizing Supply Chain Management from the University of Missouri – St. Louis. She teaches courses in International Logistics and Supply Chain Management. Dr. Zhang is a very active researcher with primary interests in modeling and optimization of transportation, logistics and supply chain systems, and she has worked with organizations in the U.S. and China. Her recent research addresses drone delivery, supply chain optimization, transportation network design, supply chain risk management, and sustainability.

Dr. Willow Yang is an Assistant Professor of Supply Chain Management at Sam Houston State University (SHSU). Dedicated to bridging the gap between academic research and industry challenges, she specializes in operations and supply chain optimization, helping organizations develop innovative, data-driven approaches to demand forecasting, procurement, inventory optimization, and distribution network design. Dr. Yang holds a patent in physical resource optimization and a provisional patent in a system designed to reduce hospital procurement costs. She received her Ph.D. in Logistics & Supply Chain Management with a minor in Marketing from the University of Missouri – St. Louis, an M.B.A. from Durham University in the UK, and a Bachelor of Engineering in Computer Science & Applications from Xi'an Jiaotong University in China. Dr. Yang brings extensive experience from the high-tech industry to her academic role, having led significant initiatives in marketing, business development, and consulting at Microsoft, HP, and IDC. Her deep industry background enriches her research and teaching with a crucial practical perspective and an emphasis on real-world relevance. She is an active contributor to academic literature and serves as a reviewer for several prestigious journals.

7. References

- Al-Nabhan, N., Alturkestani, R., Belghith, A., & AlAloula, N. (2025). A Conflict Resolution Approach for Multiple Unmanned Aerial Vehicles. *Electronics*, 14(11), 2247.
- Alrefaei, F., Alzahrani, A., Song, H., & Alrefaei, S. (2022). A survey on the jamming and spoofing attacks on the unmanned aerial vehicle networks. *2022 IEEE International IOT, Electronics and Mechatronics Conference (IEMTRONICS)*, 1–7.
- Aretoulaki, E., Ponis, S. T., & Plakas, G. (2023). Complementarity, Interoperability, and Level of Integration of Humanitarian Drones with Emerging Digital Technologies: A State-of-the-Art Systematic Literature Review of Mathematical Models. *Drones*, 7(5), 301. <https://doi.org/10.3390/drones7050301>
- Attin, A., & Bonnedahl, S. (2024). *Remote ID and Detect-and-Avoid in Unmanned-Aerial-Systems: Model Maximum Safe Speed of UAS*.
- Ayass, T., Coqueiro, T., Carvalho, T., Jailton, J., Araújo, J., & Francês, R. (2022). Unmanned aerial vehicle with handover management fuzzy system for 5G networks: Challenges and perspectives. *Intelligence & Robotics*, 2(1), 20–36.
- Bagnall, T.M., Kriz, A., Briggs, R., & Takamizawa K. (2024, September). *Demonstration and Validation of Remote ID Detect and Avoid* (Report No. BAA004). Federal Aviation Administration. https://www.faa.gov/uas/programs_partnerships/BAA/BAA004-MosaicATM-Demonstration-and-Validation-of-RID-DAA.pdf
- Battiato, S., Cantelli, L., D'Urso, F., Farinella, G. M., Guarnera, L., Guastella, D., Melita, C. D., Muscato, G., Ortis, A., & Ragusa, F. (2017). A system for autonomous landing of a UAV on a moving vehicle. *Image Analysis and Processing-ICIAP 2017: 19th International Conference, Catania, Italy, September 11-15, 2017, Proceedings, Part I* 19, 129–139.
- Bouzaïd, T., Chaib, N., Bensaad, M. L., & Oubbati, O. S. (2023). 5G network slicing with unmanned aerial vehicles: Taxonomy, survey, and future directions. *Transactions on Emerging Telecommunications Technologies*, 34(3), e4721. <https://doi.org/10.1002/ett.4721>
- Campbell, J. F., Sweeney, D., and Zhang, J. (2017). Strategic design for delivery with trucks and drones. *Supply Chain Analytics Report SCMA* (04 2017), 47–55.
- Cao, Y., Xiao, C., Cyr, B., Zhou, Y., Park, W., Rampazzi, S., Chen, Q. A., Fu, K., & Mao, Z. M. (2019). Adversarial Sensor Attack on LiDAR-based Perception in Autonomous Driving. *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security*, 2267–2281. <https://doi.org/10.1145/3319535.3339815>
- Capgemini Research Institute, 2019. The last-mile delivery challenge. Retrieved December 12th, 2020 from: <https://www.capgemini.com/wp-content/uploads/2019/01/>.
- Casalicchio, E., & Iannucci, S. (2020). The state-of-the-art in container technologies: Application, orchestration and security. *Concurrency and Computation: Practice and Experience*, 32(17), e5668. <https://doi.org/10.1002/cpe.5668>
- Changes to Type Certificates, 14 C.F.R. § 21.95 (2025). <https://www.ecfr.gov/current/title-14/chapter-I/subchapter-C/part-21/subpart-D>
- Cheng, Z., Liang, J., Choi, H., Tao, G., Cao, Z., Liu, D., & Zhang, X. (2022). Physical attack on monocular depth estimation with optimal adversarial patches. *European Conference on Computer Vision*, 514–532.

Choi, T.-M., Zhang, J., & Cheng, T. C. E. (2018). Quick Response in Supply Chains with Stochastically Risk Sensitive Retailers*: Quick Response in Supply Chains. *Decision Sciences*, 49(5), 932–957. <https://doi.org/10.1111/dec.12303>

City of Houston. (2019, March 15). *City of Houston to Pilot Pick-Up / Drop-Off Zones in Downtown's Historic District*. <https://www.houstontx.gov/parking/20190315.html>

Daganzo, C.F., 1984. The length of tours in zones of different shapes. *Transportation Research Part B: Methodological* 18(2), pp.135-145.

Davidson, D., Wu, H., Jellinek, R., Singh, V., & Ristenpart, T. (2016). Controlling {UAVs} with sensor input spoofing attacks. *10th USENIX Workshop on Offensive Technologies (WOOT 16)*.

Dorling, K., Heinrichs, J., Messier, G. G., & Magierowski, S. (2016). Vehicle routing problems for drone delivery. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 47(1), 70–85.

Dukowitz, Z. (2025, April 1). *Can you fly a drone over private property? [New for 2025]*. UAV Coach. <https://uavcoach.com/drone-over-private-property/>

Evans, M. S. (2024, June 20). *Understanding property rights in the age of drone technology*. Evans Law. <https://www.msevalslaw.com/understanding-property-rights-in-the-age-of-drone-technology/>

FAA BVLOS Aviation Rulemaking Committee. (2022). *UAS BVLOS ARC Final Report*. Federal Aviation Administration. https://www.faa.gov/regulations_policies/rulemaking/committees/documents/media/UAS_BVLOS_ARC_FINAL_REPORT_03102022.pdf

Federal Aviation Administration. (1994, January 25). *Heliport design (Advisory Circular No. 150/5390-2B)*. https://www.faa.gov/documentlibrary/media/advisory_circular/150-5390-2b/150_5390_2b_part2.pdf

Federal Aviation Administration (FAA). (2021a). *Operation of small unmanned aircraft systems over people (Final Rule)*. Federal Register, 86(10), 4314-4384.

Federal Aviation Administration (FAA). (2021b). *Remote Identification of Unmanned Aircraft (Final Rule)*. Federal Register, 86(10), 4390-4595.

Federal Aviation Administration. (2014, September 30). *Heliport design (Advisory Circular No. 150/5390-2D)*. https://www.faa.gov/documentLibrary/media/Advisory_Circular/AC_150_5390_2D_Heliports.pdf

Feng, Z., Guan, N., Lv, M., Liu, W., Deng, Q., Liu, X., & Yi, W. (2020). Efficient drone hijacking detection using two-step GA-XGBoost. *Journal of Systems Architecture*, 103, 101694.

French, S. (2025, May 5) *Drone industry funding in 2025 is low: should small businesses, drone hobbyists panic?* The Drone Girl. <https://www.thedronegirl.com/2025/04/28/drone-industry-funding-in-2025/>

Fu, Z., Zhi, Y., Ji, S., & Sun, X. (2021). Remote attacks on drones vision sensors: An empirical study. *IEEE Transactions on Dependable and Secure Computing*, 19(5), 3125–3135.

Gao, Y., Liu, Y., Wen, Q., Lin, H., & Chen, Y. (2020). Secure Drone Network Edge Service Architecture Guaranteed by DAG-Based Blockchain for Flying Automation under 5G. *Sensors*, 20(21), 6209. <https://doi.org/10.3390/s20216209>

Gavi, the Vaccine Alliance. (2016, October 14). *Rwanda launches world's first national drone delivery service powered by Zipline* [Press release]. <https://www.gavi.org/news/media-room/rwanda-launches-worlds-first-national-drone-delivery-service-powered-zipline>

Ghommam, J., & Saad, M. (2017). Autonomous Landing of a Quadrotor on a Moving Platform. *IEEE Transactions on Aerospace and Electronic Systems*, 53(3), 1504–1519. <https://doi.org/10.1109/TAES.2017.2671698>

Głąbowski, M., Sobieraj, M., & Stasiak, M. (2024). Analytical Model of the Connection Handoff in 5G Mobile Networks with Call Admission Control Mechanisms. *Sensors*, 24(2), 697. <https://doi.org/10.3390/s24020697>

Goodchild, A., & Toy, J. (2018). Delivery by drone: An evaluation of unmanned aerial vehicle technology in reducing CO 2 emissions in the delivery service industry. *Transportation Research Part D: Transport and Environment*, 61, 58–67. <https://doi.org/10.1016/j.trd.2017.02.017>

Government Accountability Office (GAO). (2020). *Unmanned Aircraft Systems: FAA Could Better Manage Safety Risks* (GAO-20-29). U.S. Government Printing Office.

Greenawalt, T. (2024, December 11). *Amazon has launched our most advanced delivery drone yet—here's everything you need to know*. About Amazon. <https://www.aboutamazon.com/news/operations/mk30-drone-amazon-delivery-packages>

HeliExperts International. (n.d.). *Heliports: 25 frequently asked questions & answers*. <https://heliexpertsinternational.com/heliport-safety-educational-and-regulatory-information/heliports-25-frequently-asked-questions-answers/>

Herath, H. M. C. W. B., Herath, H. M. S., Sumangala, S. W., De Silva, O., Chathuranga, D., & Lalitharatne, T. D. (2017). Design and development of an automated battery swapping and charging station for Multirotor Aerial Vehicles. *2017 17th International Conference on Control, Automation and Systems (ICCAS)*, 356–361. <https://doi.org/10.23919/ICCAS.2017.8204465>

Hert, D., Baca, T., Petracek, P., Kratky, V., Penicka, R., Spurny, V., Petrlik, M., Vrba, M., Zaitlik, D., Stoudek, P., Walter, V., Stepan, P., Horyna, J., Pritzl, V., Sramek, M., Ahmad, A., Silano, G., Licea, D. B., Stibinger, P., ... Saska, M. (2023). MRS Drone: A Modular Platform for Real-World Deployment of Aerial Multi-Robot Systems. *Journal of Intelligent & Robotic Systems*, 108(4), 64. <https://doi.org/10.1007/s10846-023-01879-2>

Hu, Z., Chen, H., Lyons, E., Solak, S., & Zink, M. (2024). Towards sustainable UAV operations: Balancing economic optimization with environmental and social considerations in path planning. *Transportation Research Part E: Logistics and Transportation Review*, 181, 103314.

Isik, O. K., Petrunin, I., & Tsourdos, A. (2024). Machine Learning-Based Environment-Aware GNSS Integrity Monitoring for Urban Air Mobility. *Drones*, 8(11), 690. <https://doi.org/10.3390/drones8110690>

Jahani, H., Khosravi, Y., Kargar, B., Ong, K.-L., & Arisian, S. (2025). Exploring the role of drones and UAVs in logistics and supply chain management: A novel text-based literature review. *International Journal of Production Research*, 63(5), 1873–1897. <https://doi.org/10.1080/00207543.2024.2373425>

Janßen, M., Pfandzelter, T., Wang, M., & Bermbach, D. (2023). Supporting UAVs with Edge Computing: A Review of Opportunities and Challenges. *arXiv Preprint arXiv:2310.11957*.

Jeong, J., Kim, D., Jang, J., Noh, J., Song, C., & Kim, Y. (2023). Un-Rocking Drones: Foundations of Acoustic Injection Attacks and Recovery Thereof. *Proceedings 2023 Network*

and Distributed System Security Symposium. Network and Distributed System Security Symposium, San Diego, CA, USA. <https://doi.org/10.14722/ndss.2023.24112>

Junaid, A., Konoiko, A., Zweiri, Y., Sahinkaya, M., & Seneviratne, L. (2017). Autonomous Wireless Self-Charging for Multi-Rotor Unmanned Aerial Vehicles. *Energies*, 10(6), 803. <https://doi.org/10.3390/en10060803>

Karak, A., & Abdelghany, K. (2019). The hybrid vehicle-drone routing problem for pick-up and delivery services. *Transportation Research Part C: Emerging Technologies*, 102, 427–449. <https://doi.org/10.1016/j.trc.2019.03.021>

Kelley, N. (2013, December 2). *Delivery by drone – Get your amazon order in 30 minutes*. <https://www.outsideonline.com/outdoor-adventure/delivery-drone>

Khan, S. Z., Mohsin, M., & Iqbal, W. (2021). On GPS spoofing of aerial platforms: A review of threats, challenges, methodologies, and future research directions. *PeerJ Computer Science*, 7, e507.

Kim, J., & Atkins, E. (2022). Airspace geofencing and flight planning for low-altitude, urban, small unmanned aircraft systems. *Applied Sciences*, 12(2), 576.

Kong, P.-Y. (2021). A Survey of Cyberattack Countermeasures for Unmanned Aerial Vehicles. *IEEE Access*, 9, 148244–148263. <https://doi.org/10.1109/ACCESS.2021.3124996>

Lemardelé, C., Estrada, M., Pagès, L., & Bachofner, M. (2021). Potentialities of drones and ground autonomous delivery devices for last-mile logistics. *Transportation Research Part E: Logistics and Transportation Review*, 149, 102325. <https://doi.org/10.1016/j.tre.2021.102325>

Loyalty Drones Team. (2024, October 17). *Zipline expands drone delivery with Walmart partnership*. Loyalty Drones. <https://www.loyaltydrones.com/zipline-expands-drone-delivery-with-walmart-partnership/>

Magdolna, F. (2024, July 9). *Drone Regulations - Upcoming Changes in America (2025)*. Fly Eye. <https://www.flyeye.io/drone-regulations-upcoming-changes-in-america-year/>

Matternet. (n.d.). *Milestones*. Retrieved June 28, 2025, from <https://www.matternet.com/milestones>

McNabb, M. (2022, March 1). *Wing Drone Delivery in Australia: One Drone Delivery Every 25 Seconds, Commercial Ops at Scale*. DroneLife. <https://dronelife.com/2022/03/01/wing-drone-delivery-in-australia/>

McNabb, M. (2025, March 21). *FAA signals momentum for BVLOS rulemaking: What it means for commercial drone applications*. DroneLife. <https://dronelife.com/2025/03/21/faa-signals-momentum-for-bvlos-rulemaking-what-it-means-for-commercial-drone-applications/>

Meng, W., Zhang, X., Zhou, L., Guo, H., & Hu, X. (2025). Advances in UAV Path Planning: A Comprehensive Review of Methods, Challenges, and Future Directions. *Drones*, 9(5), 376. <https://doi.org/10.3390/drones9050376>

Mesgarpour, M., Landa-Silva, D., & Dickinson, I. (2013). Overview of telematics-based prognostics and health management systems for commercial vehicles. *Activities of Transport Telematics: 13th International Conference on Transport Systems Telematics, TST 2013, Katowice-Ustroń, Poland, October 23–26, 2013, Selected Papers 13*, 123–130.

MN Shipping (n.d.). *China drone logistics revolution in 2025*. <https://mnshipping.com.vn/china-drone-logistics-revolution/>

- Mohsan, S. A. H., Othman, N. Q. H., Li, Y., Alsharif, M. H., & Khan, M. A. (2023). Unmanned aerial vehicles (UAVs): Practical aspects, applications, open challenges, security issues, and future trends. *Intelligent Service Robotics*, 16(1), 109–137. <https://doi.org/10.1007/s11370-022-00452-4>
- Muna, S. I., Mukherjee, S., Namuduri, K., Compere, M., Akbas, M. I., Molnár, P., & Subramanian, R. (2021). Air corridors: Concept, design, simulation, and rules of engagement. *Sensors*, 21(22), 7536.
- Murray, C. C., & Chu, A. G. (2015). The flying sidekick traveling salesman problem: Optimization of drone-assisted parcel delivery. *Transportation Research Part C: Emerging Technologies*, 54, 86–109. <https://doi.org/10.1016/j.trc.2015.03.005>
- National Aeronautics and Space Administration. (2018, March). *Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept of Operations v1.0*. <https://www.nasa.gov/wp-content/uploads/2024/04/2018-utm-conops-v1-0-508.pdf>
- National Aeronautics and Space Administration. (n.d.). *Unmanned Aircraft System Traffic Management (UTM)*. Retrieved June 21, 2025, from https://www.faa.gov/uas/advanced_operations/traffic_management
- National Institute of Standards and Technology (NIST). (2022). *Foundational PNT Profile – Applying the Cybersecurity Framework for the Responsible Use of Positioning, Navigation, and Timing (PNT) Services* (NIST IR 8323 Revision 1).
- Nayfeh, M., Li, Y., Shamaileh, K. A., Devabhaktuni, V., & Kaabouch, N. (2023). Machine Learning Modeling of GPS Features with Applications to UAV Location Spoofing Detection and Classification. *Computers & Security*, 126, 103085. <https://doi.org/10.1016/j.cose.2022.103085>
- Otto, A., Agatz, N., Campbell, J., Golden, B., & Pesch, E. (2018). Optimization approaches for civil applications of unmanned aerial vehicles (UAVs) or aerial drones: A survey. *Networks*, 72(4), 411–458. <https://doi.org/10.1002/net.21818>
- Petritoli, E., Leccese, F., & Ciani, L. (2018). Reliability and Maintenance Analysis of Unmanned Aerial Vehicles. *Sensors*, 18(9), 3171. <https://doi.org/10.3390/s18093171>
- Poikonen, S., & Campbell, J. F. (2021). Future directions in drone routing research. *Networks*, 77(1), 116–126. <https://doi.org/10.1002/net.21982>
- PRNewswire. (2024, July 17). *Taking donuts off the beaten path and into the skies: Manna drone delivery partners with Offbeat Donut Co.* [Press release]. <https://www.prnewswire.co.uk/news-releases/taking-donuts-off-the-beaten-path-and-into-the-skies-manna-drone-delivery-partners-with-offbeat-donut-co-302198346.html>
- Quinonez, R., Giraldo, J., Salazar, L., Bauman, E., Cardenas, A., & Lin, Z. (2020). {SAVIOR}: Securing autonomous vehicles with robust physical invariants. *29th USENIX Security Symposium (USENIX Security 20)*, 895–912.
- Ruseno, N., Lin, C.-Y., & Chang, S.-C. (2022). Uas traffic management communications: The legacy of ads-b, new establishment of remote id, or leverage of ads-b-like systems? *Drones*, 6(3), 57.
- Sathaye, H., LaMountain, G., Closas, P., & Ranganathan, A. (2022). SemperFi: Anti-spoofing GPS Receiver for UAVs. *Proceedings 2022 Network and Distributed System Security Symposium*. Network and Distributed System Security Symposium, San Diego, CA, USA. <https://doi.org/10.14722/ndss.2022.23071>

Shumaker, Loop & Kendrick, LLP. (2018). *Client Alert: FAA Drone Manufacturers Must Self-Regulate*. <https://www.shumaker.com/insight/client-alert-faa-drone-manufacturers-must-self-regulate/>

Si, J., Li, B., Wang, L., Deng, C., Wang, J., & Wang, S. (2024). A UAV Autonomous Landing System Integrating Locating, Tracking, and Landing in the Wild Environment. *Journal of Intelligent & Robotic Systems*, 110(2), 51. <https://doi.org/10.1007/s10846-023-02041-8>

Sieb, P., Michelmann, J., Flöter, F., & Wicke, K. (2023). Identifying challenges in maintenance planning for on-demand UAM fleets using agent-based simulations. *CEAS Aeronautical Journal*, 14(3), 637–660. <https://doi.org/10.1007/s13272-023-00665-y>

Singh, G., Pashchapur, R. A., & Ballal, H. (2024). Recent Trends on UAS-UTM Ecosystem and Integration Challenges. *2024 International Conference on Unmanned Aircraft Systems (ICUAS)*, 529–537. <https://doi.org/10.1109/ICUAS60882.2024.10556851>

Sohail, A. M., Khattak, K. S., Khan, Z. H., Gulliver, T. A., & Altamimi, A. B. (2025). *Exploring Vehicle Telematics in Intelligent Transportation Systems: Applications, Challenges, and Prospects*. Engineering. <https://doi.org/10.20944/preprints202504.1105.v1>

Supply Chain Brain. (2024, August 21). *Walmart to end drone deliveries in three states*. <https://www.supplychainbrain.com/articles/40239-walmart-to-end-drone-delivery-services-in-three-states>

The Rock Robotic Team. (2024, January 22). *Understanding FAA regulations for beyond visual line of sight (BVLOS) drone operations*. Rock Robotic Blog. <https://www.rockrobotic.com/post/understanding-faa-regulations-for-beyond-visual-line-of-sight-bvlos-drone-operations>

Thomas, P. R., & Sarhadi, P. (2024). Geofencing motion planning for unmanned aerial vehicles using an anticipatory range control algorithm. *Machines*, 12(1), 36.

Tian, J., Scaife, N., Kumar, D., Bailey, M., Bates, A., & Butler, K. (2018). SoK: “Plug & Pray” Today – Understanding USB Insecurity in Versions 1 Through C. *2018 IEEE Symposium on Security and Privacy (SP)*, 1032–1047. <https://doi.org/10.1109/SP.2018.00037>

Tlili, F., Ayed, S., & Chaari Fourati, L. (2024). Exhaustive distributed intrusion detection system for UAVs attacks detection and security enforcement (E-DIDS). *Computers & Security*, 142, 103878. <https://doi.org/10.1016/j.cose.2024.103878>

Tu, Y.-J., & Piramuthu, S. (2024). Security and privacy risks in drone-based last mile delivery. *European Journal of Information Systems*, 33(5), 617–630.

UAV Navigation. (2021, July 26). *Jamming and Spoofing: Two Threats for Your UAS GNC System*. UAV Navigation Blog. <https://www.uavnavigation.com/company/blog/jamming-and-spoofing-two-threats-your-uas-gnc-system>

UPS. (2017, February 21). *UPS tests residential delivery via drone launched from atop package car* [Press release]. GlobeNewswire. <https://www.globenewswire.com/news-release/2017/02/21/925955/0/en/UPS-Tests-Residential-Delivery-Via-Drone-Launched-From-Atop-Package-Car.html>

UPS. (2019, March 26). *UPS Partners With Matternet To Transport Medical Samples Via Drone Across Hospital System In Raleigh, N.C.* GlobeNewswire. <https://www.globenewswire.com/news-release/2019/03/26/1768528/30428/en/UPS-Partners->

With-Matternet-To-Transport-Medical-Samples-Via-Drone-Across-Hospital-System-In-Raleigh-N-C.html

UPS. (2019, October 1). *UPS Flight Forward attains FAA's first full approval for drone airline* [Press release]. GlobeNewswire. <https://www.globenewswire.com/news-release/2019/10/01/1923490/30428/en/UPS-Flight-Forward-Attains-FAA-s-First-Full-Approval-For-Drone-Airline.html>

U.S. Department of Transportation. (2019, October 1). *U.S. transportation secretary Elaine L. Chao announces FAA certification of UPS Flight Forward as an air carrier* [Press release]. Federal Aviation Administration. <https://www.faa.gov/newsroom/us-transportation-secretary-elaine-l-chao-announces-faa-certification-ups-flight-forward>

Varshosaz, M., Afary, A., Mojaradi, B., Saadatseresht, M., & Ghanbari Parmehr, E. (2019). Spoofing detection of civilian UAVs using visual odometry. *ISPRS International Journal of Geo-Information*, 9(1), 6.

Virginia Tech Mid-Atlantic Aviation Partnership. (2021, April). *Perspectives on drone delivery*. Virginia Tech. https://maap.ictas.vt.edu/content/dam/maap_ictas_vt_edu/Perspectives-on-drone-delivery.pdf

Voznesenskii, E. A. (2021). Automated Battery Charging System for Multi-Rotor Aerial Vehicles. *2021 Wave Electronics and Its Application in Information and Telecommunication Systems (WECONF)*, 1–4. <https://doi.org/10.1109/WECONF51603.2021.9470571>

Wang, J., & Liu, J. (2022). Secure and Reliable Slicing in 5G and Beyond Vehicular Networks. *IEEE Wireless Communications*, 29(1), 126–133. <https://doi.org/10.1109/MWC.001.2100282>

Walmart. (2021, June 17). *Walmart invests in DroneUp, the nationwide on-demand drone delivery provider*. Walmart Corporate. <https://corporate.walmart.com/news/2021/06/17/walmart-invests-in-droneup-the-nationwide-on-demand-drone-delivery-provider>

Walmart. (2023, January 5). *Walmart now operates drone delivery in 7 states, completes 6,000 drone deliveries* [Press release]. Business Wire. <https://www.businesswire.com/news/home/20230105005929/en/Walmart-Now-Operates-Drone-Delivery-in-7-States-Completes-6000-Drone-Deliveries>

Walmart. (2025, June 5). *Walmart Takes Flight With Drone Delivery Expansion to Five New Cities, Redefining Fast, Flexible Retail*. Corporate Newsroom. <https://corporate.walmart.com/newsroom/2025/06/05/walmart-takes-flight-with-drone-delivery-expansion-to-five-new-cities-redefining-fast-flexible-retail>

Wei, X., Ma, J., & Sun, C. (2024). A Survey on Security of Unmanned Aerial Vehicle Systems: Attacks and Countermeasures. *IEEE Internet of Things Journal*, 11(21), 34826–34847. <https://doi.org/10.1109/JIOT.2024.3429111>

Wei, X., & Wang, L. (2023). SigFeaDet: Signal Features-based UAV GPS Spoofing Detection using Machine Learning. *2023 IEEE 29th International Conference on Parallel and Distributed Systems (ICPADS)*, 2202–2209. <https://doi.org/10.1109/ICPADS60453.2023.00297>

Wei, X., Xu, Y., Zhang, H., Sun, C., Li, X., Huang, F., & Ma, J. (2025). Sensor attack online classification for UAVs using machine learning. *Computers & Security*, 150, 104228. <https://doi.org/10.1016/j.cose.2024.104228>

Wing. (2019, April 23). *Wing becomes first certified Air Carrier for drones in the US* [Press release]. <https://wing.com/news/wing-becomes-first-certified-air>

- Xing, L., & Johnson, B. W. (2023). Reliability Theory and Practice for Unmanned Aerial Vehicles. *IEEE Internet of Things Journal*, 10(4), 3548–3566.
<https://doi.org/10.1109/JIOT.2022.3218491>
- Yue, K. (2024). Multi-sensor data fusion for autonomous flight of unmanned aerial vehicles in complex flight environments. *Drone Systems and Applications*, 12, 1–12.
- Zemlianko, H., & Kharchenko, V. (2023). *Cybersecurity risk analysis of multifunctional UAV fleet systems: A conceptual model and IMECA-based technique*.
- Zhang, J., Campbell, J. F., & Sweeney II, D. C. (2024). A continuous approximation approach to integrated truck and drone delivery systems. *Omega*, 126, 103067.
- Zhang, J., Campbell, J. F., Sweeney II, D. C., & Hupman, A. C. (2021). Energy consumption models for delivery drones: A comparison and assessment. *Transportation Research Part D: Transport and Environment*, 90, 102668.
- Zipline. (n.d.). *Zipline Fact Sheet*. Retrieved June 28, 2025, from <https://www.zipline.com/about/zipline-fact-sheet>

8. Appendix A. Modeling Framework and Scenarios Data

Modeling Assumptions

Items are delivered from a single depot to customers in a compact region. The delivery region is assumed circular with radius R , a central depot, and a uniform customer distribution with density δ . Drones are assumed to have a payload capacity of one unit, while trucks have higher capacities of m_t ($m_t \gg 1$). Trucks are assumed to be utilized to full capacity, and the number of customers in the delivery region is large compared with m_t . Thus, the delivery region can be partitioned into multiple zones. For zones far from the depot, there exists linehaul travel to and from the delivery zone. In contrast, zones that include the depot require no linehaul travel. When the number of truck routes $N(= \frac{\delta \pi R^2}{m_t})$ is greater than five, a linehaul will be considered, and the expected linehaul distance between the depot to the delivery zone is $\frac{4R}{3}$. And linehaul isn't considered when $N \leq 5$. Let $F = 1, \text{ if } N > 5; \text{ otherwise, } F = 0$.

Continuous approximation method, specifically the swath strategy proposed in Daganzo (1984), is used to estimate the expected delivery cost and emissions for truck-only and truck-drone delivery.

Truck-Only Delivery

In truck-only delivery, a truck departs from the depot, visits all customers delivering one item to each customer, and then returns back to the depot. The expected vertical distance between two adjacent stops is $\frac{1}{\delta w}$, and the expected horizontal distance between two adjacent stops is $\frac{w}{3}$. Thus, the optimal swath width that minimizes the expected distance is $w_{to}^* = \sqrt{\frac{3}{\delta}}$.

The expected optimal total cost per delivery using truck-only delivery depends on the delivery density δ and the truck parameters (c_t, m_t), and is given by

$$C_{to}^*(\delta, c_t, m_t) = \frac{4c_t F R}{3m_t} + \frac{2c_t}{\sqrt{3}\delta} \quad (1)$$

where c_t is the total cost per unit of distance traveled by the truck. This cost c_t includes non-fuel, fuel, and emissions components:

$$c_t = \rho_t + f_t(p_t + p_e e_t), \quad (2)$$

where:

- ρ_t is the non-fuel variable cost per unit of distance (e.g., \$/mile),
- f_t is the amount of fuel (diesel) consumption per unit distance (e.g., gallon/mile),

- p_t is the cost of fuel (diesel) per unit of fuel (e.g., \$/gallon),
- e_t is the amount of emissions per unit of fuel (diesel) consumed (e.g., kg CO2e/gallon),
- p_e is the cost of emissions per unit released (e.g., \$/kg CO2e).

Note as with p_t , expression $p_e e_t$ indicates the cost of emissions in \$ per gallon of diesel.

With this expected optimal total cost model, the expected optimal operating cost per delivery (C_{to}^o) and the expected optimal emissions per delivery (C_{to}^e) in kg CO2e for truck-only delivery are as follows:

$$C_{to}^o = \frac{4c_t^o FR}{3m_t} + \frac{2c_t^o}{\sqrt{3\delta}}, \quad (3)$$

$$C_{to}^e = \frac{4c_t^e FR}{3m_t} + \frac{2c_t^e}{\sqrt{3\delta}}, \quad (4)$$

where $c_t^o = \rho_t + p_t f_t$, and $c_t^e = f_t e_t$.

Drone-Only Delivery

In drone-only delivery, a drone departs from the depot, visits one customer, and returns to the depot. The expected total cost per delivery using drone-only delivery depends on the drone flight range R_d and the drone unit cost c_d , and is given by

$$C_{do}(c_d, R_d) = \frac{4c_d}{3} R_d. \quad (5a)$$

Suppose the drones in DO can make m_d stops per trip (an on-going research in both academic and industry) where $1 \leq m_d \leq 5$, we use the formulas provided in Campbell (1993), which is given by

$$C_{do}(c_d, m_d, R_d) = \frac{4c_d}{3m_d} R_d + c_d K \delta^{-1/2}, \quad (5b)$$

where constant K is given in the following table:

Table 1. Values of K

m_d	1	2	3	4	5	≥ 6
K	0	0.73	0.68	0.63	0.60	0.57

Parameter c_d is the total cost per unit of distance traveled by the drone, defined as:

$$c_d = \rho_d + f_d(p_d + p_e e_d). \quad (6)$$

where:

- ρ_d is the non-fuel variable cost per unit of distance (e.g., \$/mile),
- f_d is the amount of fuel (electricity) consumption per unit distance (e.g., kWh/mile),
- p_d is the cost of fuel (electricity) per unit of fuel (e.g., \$/kWh),
- e_d is the amount of emissions per unit of fuel (electricity) consumed (e.g., kg CO2e/kWh),
- p_e is the cost of emissions per unit released (e.g., \$/kg CO2e).

Similarly, the operating cost (C_{do}^o) and emissions (C_{do}^e) for drone-only delivery are as follows:

$$C_{do}^o = \frac{4c_d^o}{3m_d} R_d + K c_d^o \delta^{-1/2}. \quad (7)$$

$$C_{do}^e = \frac{4c_d^e}{3m_d} R_d + K c_d^e \delta^{-1/2}. \quad (8)$$

where $c_d^o = \rho_d + p_d f_d$, and $c_d^e = f_d e_d$.

Truck-Drone Delivery

In hybrid truck-drone delivery, more than one drone departing from the truck, each making one delivery, and then returns to the truck at the next truck delivery stop. The truck also makes deliveries concurrently with the drones. In our truck-drone model, we consider a situation where a truck carries n ($n \geq 1$) drones, each drone makes one delivery before the truck makes a delivery, and the truck and drone make deliveries along a swath, as shown in Figure A1. The dashed line depicts the drone travel, and the circles depict the drone deliveries; while the solid line depicts the truck travel, and the squares depict the truck deliveries.

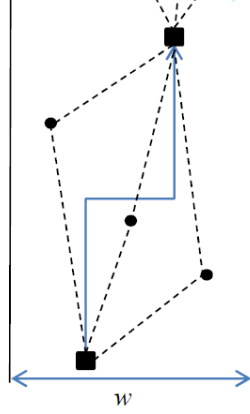


Figure A1. Truck-drone delivery with three drones in one delivery cycle

Consider a delivery cycle that begins with the truck and drone together at a customer location (which has already been visited by the truck in the previous delivery cycle) and contains n drone deliveries and one truck delivery at the end of the cycle (i.e., total number of deliveries in one delivery cycle is $n + 1$). A truck-drone delivery route can be viewed as a collection of these cycles (the last cycle in the route has the depot as the endpoint instead of a customer). The drones travel in Euclidean (L2) distance and makes n deliveries. For the i^{th} drone delivery, the expected vertical and horizontal distance of the outbound travel leg is $\frac{i}{\delta w}$ and $\frac{w}{3}$, respectively, while the expected vertical and horizontal distance of the inbound travel leg is $\frac{n+1-i}{\delta w}$ and $\frac{w}{3}$, respectively. Thus, the expected drone travel distance per delivery in a cycle is then $\frac{n}{n+1} \left[\frac{2w}{3} + \frac{n+1}{\delta w} \times \varphi(\delta w^2) \right]$. For the truck, the expected vertical distance in one cycle is $\frac{n+1}{\delta w}$, while the expected horizontal distance is $\frac{w}{3}$. The expected truck local travel distance per delivery in a cycle is then $\frac{w}{3(n+1)} + \frac{1}{\delta w}$.

There are m_t deliveries per truck-drone route in total, so the expected truck and drone travel distance per delivery for truck-drone service, $VMTD_{td}$, can be approximated as

$$VMTD_{td} = \frac{1}{n+1} \frac{w}{3} + \frac{1}{\delta w} + \frac{2n}{n+1} \frac{w}{3} + \frac{n}{\delta w} \times \varphi(\delta w^2). \quad (9a)$$

Like in DO, suppose drones can make m_d stops per trip, each drone makes the deliveries in the same sequence (e.g., we have two 2-stop drones, and the delivery sequence is Truck's stop $\rightarrow$ Drone1's 1st stop $\rightarrow$ Drone2's 1st stop $\rightarrow$ Drone1's 2nd stop $\rightarrow$ Drone2's 2nd stop $\rightarrow$ Truck's next stop), the expected truck and drone travel distance per delivery for truck-drone service, $VMTD_{td}$, can be approximated as

$$VMTD_{td} = \frac{1}{nm_d+1} \frac{w}{3} + \frac{1}{\delta w} + \frac{nm_d(m_d+1)}{nm_d+1} \frac{w}{3} + \frac{nm_d}{\delta w} \times \varphi(\delta w^2). \quad (9b)$$

The expected cost per delivery for truck-drone delivery, C_{td} , is then

$$C_{td} = c_t \left(\frac{1}{nm_d+1} \frac{w}{3} + \frac{1}{\delta w} \right) + c_d \left[\frac{nm_d(m_d+1)}{nm_d+1} \frac{w}{3} + \frac{nm_d}{\delta w} \times \varphi(\delta w^2) \right]. \quad (10)$$

Expression (10) is a convex function of the swath width w . Note that δw^2 is the number of deliveries in a square with side length equal to the swath width. Suppose we use $k = w\sqrt{\frac{\delta}{3}}$, which allows us to relate one parameter k to the number of deliveries in a square with side length equal to the swath width (since $3k^2 = \delta w^2$). We rewrite the local costs of C_{td} in terms of δ and k :

$$\begin{aligned} & c_t \left(\frac{1}{nm_d+1} \frac{w}{3} + \frac{1}{\delta w} \right) + c_d \left[\frac{nm_d(m_d+1)}{nm_d+1} \frac{w}{3} + \frac{nm_d}{\delta w} \times \varphi(\delta w^2) \right] \\ &= c_t \frac{1}{\sqrt{3\delta}} \left[\frac{k}{nm_d+1} + \frac{1}{k} + \frac{c_d}{c_t} \left(\frac{nm_d(m_d+1)k}{nm_d+1} + \frac{nm_d}{k} \times \varphi(3k^2) \right) \right]. \quad (11) \end{aligned}$$

The right side of expression (11) suggests that the optimal k does not depend on the delivery density δ , but does depend on the ratio $\frac{c_d}{c_t}$ and the number of drone deliveries (n) in a cycle.

The expected optimal cost of serving a customer at distance r using truck-drone delivery depends on r , the delivery density δ , the truck parameters (c_t, m_t), drone parameters (c_d, n) and is given by

$$C_{td}^*(r, \delta, c_t, c_d, m_t, m_d, n) = \frac{4c_t FR}{3m_t} + \frac{c_t}{\sqrt{3\delta}} \left[\frac{k}{nm_d+1} + \frac{1}{k} + \frac{c_d}{c_t} \left(\frac{nm_d(m_d+1)k}{nm_d+1} + \frac{nm_d}{k} \times \varphi(3k^2) \right) \right]. \quad (12)$$

Similarly, the operating cost (C_{td}^o) and emissions (C_{td}^e) for truck-drone delivery are as follows:

$$C_{td}^o = \frac{4c_t^o}{3m_t} FR + \left[\frac{k}{nm_d+1} + \frac{1}{k} + \frac{c_d}{c_t} \left(\frac{nm_d(m_d+1)k}{nm_d+1} + \frac{nm_d}{k} \times \varphi(3k^2) \right) \right] \frac{c_t^o}{\sqrt{3\delta}}. \quad (13)$$

$$C_{td}^e = \frac{4c_t^e}{3m_t} FR + \left[\frac{k}{nm_d+1} + \frac{1}{k} + \frac{c_d}{c_t} \left(\frac{nm_d(m_d+1)k}{nm_d+1} + \frac{nm_d}{k} \times \varphi(3k^2) \right) \right] \frac{c_t^e}{\sqrt{3\delta}}. \quad (14)$$

Parameter Estimation

Baseline parameter estimates (as shown in Table 1) are drawn from established literature. For trucks, we assume a typical Class 4 diesel delivery truck with a fuel efficiency of 11.5 miles per gallon of diesel, i.e., $f_t = 0.087$ gallon per mile (Stolaroff et al., 2018), and a fuel cost of $p_t = \$3.826$ per gallon of diesel (EIA, 2024). The non-fuel operating cost is $\rho_t = \$1.937$ per mile, which includes labor, maintenance, depreciation, etc. (ATRI, 2024). The truck emits $e_t = 13.35$ kg CO₂e per gallon of diesel consumed in its lifecycle. Each truck has a delivery capacity of 100 packages per trip, which reflects typical last-mile delivery operations. For drones, the fuel efficiency of a delivery drone is assumed to be $f_d = 0.057$ kWh per mile (Kirchstein, 2018), with an electricity cost of \$0.167 per kWh (EIA, 2024). We estimate a non-fuel operating cost of \$0.091 per mile based on Zhang et al. (2024), which accounts for labor, drone maintenance, battery replacement, and bandwidth costs. The drone's lifecycle emissions depend on electricity generation, with a national average carbon intensity of $e_d = 0.654$ kg CO₂e per kWh (Stolaroff et al., 2018). We set the baseline number of drones per truck to be one. The baseline delivery density is set at 25 deliveries per square mile, representing suburban environments such as Minneapolis (Gulden, 2017). The carbon price is initially set to zero, so that total costs in the baseline scenario reflect operational costs only.

Table 1. Baseline Value for Truck and Drone Parameters

	f_j	p_j	ρ_j	e_j	m_j
Truck ($j = "t"$)	0.087 gallon/mile	3.826 \$/gallon	1.937 \$/mile	13.35 kg CO ₂ e/gallon	100 units
Drone ($j = "d"$)	0.057 kWh/mile	0.167 \$/kWh	0.091 \$/mile	0.654 kg CO ₂ e/kWh	1 unit

Truck Fuel Type	f_t	p_t	ρ_t	e_t
Diesel	0.087 gallon/mile	3.826 \$/gallon	1.937 \$/mile	13.35 kg CO ₂ e/gallon
Compressed Natural Gas (CNG)	0.093 GGE/mile	2.99 \$/GGE	1.937 \$/mile	9.34 kg CO ₂ e/GGE
Electricity	1.417 kWh/mile	0.167 \$/kWh	1.937 \$/mile	0.654 kg CO ₂ e/kWh

Table 2. Parameter values for sensitivity analysis

Category	Key Parameters	Low Value	Baseline	High Value
Drone-related	Drone Non-fuel Operating Cost, ρ_d (\$/mile)	0.018	0.091	0.455
	Drone Energy Consumption, f_d (kWh/mile)	0.011	0.057	0.285
	Drone Payload Capacity, m_d (units)	-	1	2
Truck-related	Number of Drones per Truck (units)	-	1	2, 4
	Truck Payload Capacity (units)	50	100	150
	Truck Fuel Type	Compressed Natural Gas, Electricity	Diesel	-
Region-related	Delivery Region Size, R (mile)	2, 5	10	-
	Delivery Density, δ (# deliveries/sq. mile)	1	25	625
	Carbon Intensity of Electricity e_d (kg CO2e/kWh)	0.367	0.654	0.913



INSTITUTE FOR HOMELAND SECURITY

The Institute for Homeland Security at Sam Houston State University is focused on building strategic partnerships between public and private organizations through education and applied research ventures in the critical infrastructure sectors of Transportation, Energy, Chemical, Water / Wastewater, Healthcare, and Public Health.

The Institute is a center for strategic thought with the goal of contributing to the security, resilience, and business continuity of these sectors from a Texas Homeland Security perspective. This is accomplished by facilitating collaboration activities, offering education programs, and conducting research to enhance the skills of practitioners specific to natural and human caused Homeland Security events.

[Institute for Homeland Security](#)
[Sam Houston State University](#)

© 2025 The Sam Houston State University Institute for Homeland Security

Zhang, J., & Yang, W. (2025). Truck-Drone Delivery Systems: Assessing Emerging Risks and Opportunities in Transportation Logistics (Institute for Homeland Security Report No. 2025-1026). Institute for Homeland Security.
<https://doi.org/10.17605/OSF.IO/3ZD7C>