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Risk-Mitigation Strategies for Autonomous Delivery Vehicles in the Last Mile: A Comprehensive Overview of the Current State and Future Potential of Autonomous Delivery Technologies in the Supply Chain

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Abstract: The delivery industry has experienced rapid expansion, driven by the substantial increase in online shopping and the growing demand for food delivery services. Despite this growth, the last stage of delivery, known as the last mile, continues to pose challenges in terms of cost-effectiveness and operational efficiency. In this manuscript, the potential of autonomous delivery vehicles (ADVs) as a viable solution to these challenges is deeply explored. ADVs have the capability to significantly reduce labor costs, improve overall delivery efficiency, and play a role in decreasing carbon emissions. However, it is crucial to recognize the potential risks that ADVs may encounter, including concerns related to technological reliability, security, and regulatory obstacles. Successfully implementing ADVs will necessitate effective risk management and mitigation strategies. The objective of this research is to investigate the potential for ADV last-mile delivery while minimizing associated risks. In addition to discussing the current state of ADVs, this study underscores the necessity for innovative risk mitigation solutions to optimize last-mile delivery and particularly emphasizes the crucial role of artificial intelligence and machine learning in the realm of route optimization and operational efficiency enhancement.

Keywords: supply chain, autonomous delivery vehicles, drones, risk mitigation

1. Introduction

Over the last five years, the delivery industry has seen substantial growth, with 20.2 billion retail packages being delivered annually. This demand offers significant revenue opportunities for operators, with package and food delivery markets amounting to $171 billion and $150 billion, respectively. However, despite the industry's revenue potential, many aspects of delivery remain unprofitable. Most food delivery platforms, such as DoorDash and Uber Eats, are losing more money than they make. The primary financial challenge for the industry is labor, particularly in the last mile of service, which accounts for approximately half of the total shipping cost [1].

Labor costs range from $16 per hour to $100,000 per year, with labor shortages, exacerbated by the pandemic, intensifying the problem. Given these challenges, transportation and tech leaders are looking to vehicle autonomy to achieve future growth and profitability. They are working together to introduce self-driving delivery vehicles on American roads, sidewalks, and airspace, as the potential financial rewards are significant. The rise of autonomous delivery vehicles (ADVs) presents both an opportunity and a challenge for urban policymakers. Many cities are grappling with increased congestion due to the growing number of delivery vehicles. Even before the pandemic, delivery volume was on the rise, and COVID-19 has only exacerbated this trend. However, this congestion has led to longer transportation times, higher carbon emissions, and safety hazards. Thankfully, ADVs have the potential to address this congestion by improving vehicle efficiency and extending operating hours. They can also be programmed to stop at designated curbs, eliminating the problem of double or triple parking. Furthermore, sidewalk robots and aerial drones can further reduce the number of vehicles on the road, leading to additional benefits. In addition, these vehicles are expected to be electric-powered, reducing their carbon footprint. Moreover, they offer safety benefits by minimizing accidents caused by human error. A recent study by the Virginia Tech Transportation Institute predicts that widespread adoption of occupant-less vehicles could reduce national road fatalities and injuries by 55–62 percent, potentially saving 34,000 American lives and preventing four million injuries annually. Most of this reduction would come from eliminating trips to a store for goods that could have been delivered. The objective of this research is to investigate the potential for ADV last-mile delivery while minimizing associated risks. The paper is in line with current interdisciplinary research areas, such as identifying and mitigating

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risks. Examples of research areas such as decision support systems and electronic commerce, IT risk management (RM) and governance, and perceived risk and usability in information systems are relevant. These areas are also linked to research topics related to electronic supply chain management. Through a careful and thorough review of the existing literature and developing several potential risk-mitigation strategies, this research fills an existing gap in the ADV and last-mile literature by suggesting mitigation strategies for ADV last-mile delivery.

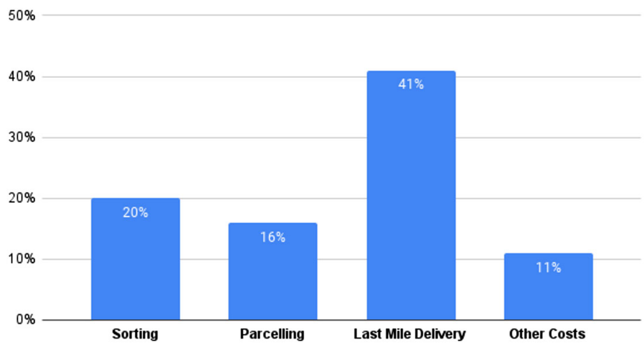
Technologies that are assisting with ADV last-mile delivery include artificial intelligence (AI) and machine learning (ML). AI technologies have proven to be invaluable for businesses and industries in analyzing complex data sets but especially in the delivery industry. It has been noted that the use of AI in delivery has assisted in cost reduction, enhanced efficiency, and improved safety [2–5]. Advancements in ML and sensor technologies make autonomous systems increasingly reliable, improve route optimization, and enhance operational efficiency [6].

This research paper is arranged in multiple sections with each section briefly described next. The concept of ADV's being used for last-mile delivery is discussed in the introduction section. A section entitled last-mile delivery is next where the paper's objective is laid out along with a basic definition of last-mile delivery. Subsequently, the literature review focusing on ADV's and last-mile delivery is presented. Different types of ADV's are discussed in the section entitled land-based ADV's. The next main section of the paper details risks and risk-mitigation strategies of ADV use including technical, legal, and public acceptance, cost, and security risks. An associated section presenting the similar details on risks regarding the use of drones for last mile delivery follows. Finally, after a brief discussion of the main findings, a conclusion contains a summary of the main paper contributions.

1.1. Last-mile delivery

The last leg of logistics, known as the last mile, is a critical part of the delivery process [7]. This aspect of the downstream supply chain links the logistics provider to the end consumer and involves the physical transfer of purchased goods [8]. The last mile involves three key stakeholders: the seller, the intermediary, and the end user [9] and is particularly susceptible to disruptions, including challenges such as widely dispersed consumers [10], complex stakeholder involvement [11], and specific delivery requests such as time windows [8]. Moreover, the last mile is notably expensive, accounting for up to 50% of logistics costs in the courier, express, and parcel industry [1, 12] (see Figure 1).

Figure 1
Supply chain costs



However, research has shown that e-commerce and home delivery can cost retailers up to 23 times more than in-store purchases [13]. The challenge lies in the discrepancy between what delivery companies are working to offer timely, customized, cost-effective services to gain a competitive edge [10], driving continuous growth and competition in the B2C delivery market [14]. Consumers are willing to pay and the actual cost of delivery, impacting profit margins [13]. Studies indicate that consumers are generally reluctant to pay extra for delivery, leaving logistics providers to cover the added costs. To attract consumers, many retailers offer "free" delivery options, but these costs are often factored into the product prices [13]. As a result, consumer expectations for faster and more efficient delivery can be unrealistic, adding pressure on producers to balance production capacities, competition, and environmental concerns [15].

Efficient and dependable last-mile freight distribution logistics play a crucial role in the supply chain. The negative impact on customer satisfaction and business operations underscores the necessity for policymakers and companies to prioritize rectifying these inefficiencies [16]. The challenges associated with last-mile delivery are projected to escalate due to the growing demand for e-commerce and consumers' heightened expectations for prompt deliveries. These trends are fueled by an increase in package volume, smaller shipment sizes, and more frequent delivery trips. The COVID-19 pandemic, changes in work patterns, and a surge in e-commerce and delivery demands have exposed critical vulnerabilities in the supply chain, such as rising disruptions, over-reliance on residential home deliveries, and labor shortages [17–19].

RM is a systematic process that companies follow to decrease the likelihood of unexpected events and maximize profit. The concept of RM is well defined by the Association for Project Management (APM) as "A process whereby decisions are made to accept known or assessed risks and the implementation of actions to reduce the consequences or probability of occurrence" [20]. According to Stranks [21], RM involves identifying, evaluating, and controlling exposure to each risk that hinders project success. Chong [22] emphasizes that risk is a fundamental aspect of RM, which aims to minimize or maintain risk at an acceptable level for the enterprise. Visualizing RM as a map of hazards and the potential harm they may cause, Chong [22] illustrates how it can help in addressing challenges caused by risks. Additionally, it underscores the crucial nature of risk identification in the risk assessment process, highlighting that any risks not recognized at the outset may remain unaddressed and pose potential problems down the line (see Table 1).

2. Literature Review

The field of technology is rapidly progressing, especially in digitalization and autonomous vehicles, with researchers achieving major breakthroughs [23]. Autonomous last-mile delivery utilizes automated technologies such as drones, robots, and self-driving vehicles to transport goods from distribution centers to their final destinations. This innovative method aims to address traditional challenges in the final phase of delivery, including traffic congestion, delays, and high operational costs. By leveraging state-of-the-art technology, companies can enhance the efficiency, speed, and sustainability of the final stage of product delivery. Autonomous vehicles are rapidly becoming commercially viable, venturing into new territories. Automated guided vehicles (AGVs) have been a fixture in warehouses for many years [24], and recently, they have appeared in the form of autonomous delivery robots (ADVs) on sidewalks. With the current trend of increasing urbanization and e-commerce, there is growing pressure to

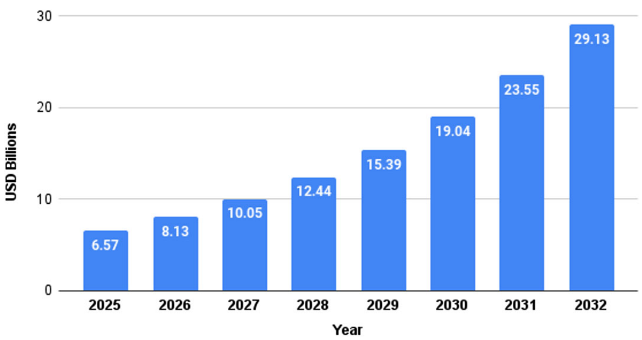
Table 1
Advantages of ADV/drone delivery methods vs. traditional delivery methods for the last-mile

Traditional delivery	ADV/Drone delivery
Delays in the project are being experienced due to the extensive amount of labor involved in the tasks. The sheer volume of work is contributing to the timeline setbacks.	When implemented correctly, reducing delivery times can have a significant impact on customer satisfaction, operational efficiency, and cost savings.
The most expensive aspect of the delivery process.	Plays a significant role in reducing long-term expenses and promoting cost-effectiveness over an extended period.
High-carbon footprint refers to the total amount of greenhouse gases, particularly carbon dioxide, released into the atmosphere as a result of human activities. This includes emissions from transportation, energy production, industrial processes, and the burning of fossil fuels.	The emissions of greenhouse gases and air pollutants can be reduced through the use of electric power in various applications, such as electric vehicles. Electric power can lead to lower emissions compared to traditional combustion engines, resulting in environmental benefits and improved air quality.
The current trend in technology is evolving toward what is being referred to as Industry 5.0, which signifies the integration of advanced technologies such as artificial intelligence, robotics, and the Internet of Things with traditional industrial processes. This convergence is expected to further revolutionize manufacturing and industrial production, leading to increased efficiency, customization, and connectivity across the entire value chain.	The broader macroeconomic trends are providing support for a shift toward autonomous and connected vehicles (ADVs). This shift is expected to be influenced by factors such as technological advancements, changing consumer preferences, and regulatory initiatives aimed at promoting sustainable and efficient transportation solutions. Fueled by swift advancements in artificial intelligence (AI), edge computing, and sensor technologies, autonomous vehicles have edged closer to becoming a reality in recent years. Various forms of highly automated vehicles have emerged in the market, and fully automated vehicles have started to undergo testing.

discover innovative solutions to enhance the efficiency of last-mile deliveries. One potential solution is the development of automated delivery systems using new and advanced technologies, which could lead to a more efficient and sustainable last-mile delivery system [25]. To tackle these challenges, companies such as Amazon, Walmart, Einride, Eliport, and UPS are exploring the use of autonomous freight delivery options [26, 27]. The market size for last-mile automated delivery technologies, encompassing ADVs, drones, and robots, is forecasted to reach over $29 billion by 2032, potentially representing up to 20% of the last-mile package delivery industry (see Figure 2).

Advancements in technology offer numerous advantages, such as increased efficiency, safety, and sustainability, and can contribute to reducing human error. Smaller-scale automated technologies, including drones and delivery robots, can provide more efficient, safer, cost-effective, and sustainable solutions compared to traditional truck deliveries by bypassing congested streets and curbsides [27]. These ADVs in urban areas will handle package delivery, groceries, drugstore items, and prepared meals. The delivery fleet will consist of various vehicles operating on roads, sidewalks, and aerial drones. There are several indicators that ADV delivery is on the horizon and should be a priority in the near term. The ongoing trend in favor of ADV delivery is supported by significant growth in home delivery. Notably, the trucking industry in the United States alone is facing a shortage of 80,000 drivers. In response, companies are raising wages substantially, with some seeing increases of 50 to 75 percent compared to 2018. However, this has led to a more pronounced shortage of workers, as drivers are using their higher earnings to reduce their time on the road. This cost environment is prompting delivery providers to implement strategies for cost reduction. Improved routing, labor scheduling, and fuel-efficient vehicles have led to productivity gains for delivery companies. The potential elimination of drivers could further improve cost structures. Advancements in driverless vehicle technology are paving the way for autonomous delivery. Developers are also working on sidewalk robots to enhance reliability and safety. Despite technical challenges, significant funding is available for the continued development of autonomous delivery technology, with billion-dollar partnerships established between various companies including Ford, Peterbilt, FedEx, UPS, Waymo, and Amazon.

Figure 2
Autonomous last-mile delivery market size



The landscape of last-mile deliveries is rapidly changing with the emergence of ADVs, drones, and robots. These technologies promise faster, more secure, and cost-effective deliveries while also reducing emissions. Businesses adopting these innovations can improve customer satisfaction, cut expenses, and gain a competitive edge. Initial costs are outweighed by long-term benefits such as reduced reliance on traditional delivery trucks. Autonomous last-mile solutions meet consumer demand for swift and convenient deliveries, leading to enhanced customer satisfaction and brand loyalty. Automation also brings lower labor expenses, optimized route planning, and reduced fuel costs, improving operational efficiency. Advancements in AI, ML, and sensor technologies make autonomous systems increasingly reliable. Furthermore, the focus on sustainability is driving the adoption of eco-friendly autonomous electric vehicles and drones, contributing to the growth of the autonomous last-mile delivery market. The last-mile delivery faces challenges like coping with e-commerce growth, ensuring efficient delivery, promoting eco-friendly solutions, handling congestion, and meeting consumer demands. Reimagining the last mile is essential for success.

2.1. Types of land-based ADVs

The landscape of autonomous delivery has evolved with the advent of delivery robots. This state-of-the-art technology offers various advantages, including enhanced efficiency, cost-effectiveness, and reduced environmental impact [28]. Despite the advanced stage of delivery robot technology, navigating public traffic and adhering to regulations concerning data protection, liability, and security present challenges for mobile robots engaged in last-mile delivery. Companies like Starship Technologies, Amazon Scout, and Nuro have already introduced delivery robots to the market. The robotics company Starship Technologies, based in Estonia, had completed more than 6 million autonomous deliveries by January 2024, indicating a consistent growth pattern since its commercial debut in 2017. The Amazon Scout electric delivery system is created to securely transport packages to customers using autonomous delivery devices. The Scout bots are compact, about the size of a small cooler, and move along sidewalks at a walking speed. Testing for Scout was first introduced to a neighborhood in Snohomish County, Washington. Following this, the self-operating delivery system has expanded to Atlanta, Georgia, and Franklin, Tennessee. Nuro specializes in creating customized ADVs designed for local communities. Their flagship vehicle, the R2, is equipped with a comprehensive array of sensors including 360° cameras, Lidar, short and long-range radar, and ultrasonic sensors. Nuro has established strategic partnerships in Houston, collaborating with Domino's for pizza deliveries, CVS for prescription deliveries, and Walmart for grocery deliveries. Notably, FedEx has recently made a significant commitment to utilize Nuro's autonomous vehicles for large-scale last-mile deliveries. The testing phase with FedEx in Houston is already underway. While delivery robots outperform drones in several aspects, they also have limitations. For example, delivery bots traverse sidewalks at a modest speed of 6 km/h and can carry packages weighing up to 10 kg. An additional advantage of robots is that a single operator can manage multiple bots, unlike drones [29]. Unlike drones, which can travel directly from one point to another, delivery robots are confined to road networks and pathways. Still, robots offer the added benefit of respecting people's privacy, unlike drones, and are less susceptible to adverse weather conditions. The implementation of robots can lead to expedited and more cost-efficient delivery services for customers [30]. ADVs primarily utilize two methods: truck-based and hub-based systems. In the direct truck-based ADV approach, a central hub is employed alongside multiple on-board ADVs. The truck visits a neighborhood, deploys and retrieves ADVs, and temporarily parks them. Upon their return, the ADVs are loaded with new freight, and the truck proceeds to the next neighborhood. This method is commonly used to serve locations that are relatively distant within a city. For instance, a van can transport a truckload of freight to a specific neighborhood and then deploy its ADV to automatically deliver the packages to customers before returning to the truck. This approach is effective in reducing delivery costs and can result in a cost reduction of up to two-thirds compared to traditional truck delivery. However, the actual cost saving varies based on factors such as driver costs and ADV prices. On the other hand, hub-based ADVs make use of small local micro-hubs in each neighborhood. Shipments are delivered to the micro-hub and held until the customer's preferred delivery time. This model is particularly popular on college campuses and in small neighborhoods, where the ADVs operate much like pedestrians. The appeal of ADVs lies in their potential to reduce operational expenses. Hofmann and Prause [9] discover that the cost of delivering a single unit using ADVs is significantly lower than that of traditional delivery services, at less than one dollar per delivery. Boysen et al. [27] also observe reduced costs, time savings, and secure deliveries with their truck-based system despite the initial investment and operating costs required by depots. These findings were corroborated by Garus et al. [31]. Moreover, Chen et al. [32] emphasize the necessity for innovative solutions to enhance last-mile deliveries and proposed that ADVs could provide a cost-effective option in specific situations. Recent research has demonstrated promising results regarding the cost-effectiveness of truck-based automated delivery vehicles (ADVs) for last-mile deliveries. According to Ostermeier et al. [33], such vehicles can lead to up to a 68% reduction in delivery costs compared to traditional truck deliveries. Similarly, Bakach et al. [29] conclude that utilizing a local hub with robots resulted in over 70% savings in operating costs when compared to standard truck deliveries, particularly beneficial when considering customer delivery time windows.

In a study conducted by Jennings and Figliozzi [34], it was found that the use of autonomous deliveries can lead to increased cost efficiency due to their time-saving advantages. The research indicated that utilizing sidewalk ADVs in the United States resulted in both time and monetary savings. Furthermore, Schaudt and Clausen [35] support these findings, highlighting that optimized distribution can result in significant cost savings, particularly in term.

In a recent study conducted by Simoni et al. [25], it was found that ADV-assisted delivery trucks yield high-quality outcomes, providing time-saving advantages for last-mile deliveries. Tesco has integrated an AI-powered vehicle routing and scheduling system, resulting in an impressive saving of 11.2 million miles and an 8% reduction in fuel consumption per order [25]. Embracing the concept of human-less last-mile delivery, Tesla has contributed to the emergence of a new AI-powered industry. Additionally, Walmart is leveraging an AI-powered vehicle route planning tool to ensure deliveries within two hours, offering the most efficient routes based on real-time factors such as weather and traffic conditions for each delivery location.

2.2. Potential risks and mitigation strategies of autonomous delivery vehicles

To succeed in the supply chain, service providers must be aware of last-mile delivery challenges and prioritize risk assessment to develop effective response strategies. According to Davison [36] and Stephenson et al. [37], RM consists of two interconnected stages: risk identification and risk analysis. During risk identification, all potential risks must be identified, while risk analysis involves determining their impact, cause, and control. The synergy between commerce and technology has endured for an extended period and continues to thrive. Advancements in Information and Communication Technology (ICT) have revolutionized numerous industries, including global commerce, leading to significant evolution and transformation in processes. However, traditional commerce is no longer adequate to meet the demands of the modern era [6]. The primary challenge for companies is to deliver exemplary service to their customers. E-commerce has various advantages for customers, including access to a wider range of products, better pricing, and convenience. Last-mile delivery is crucial for customer satisfaction and environmental impact. Efficient planning and innovative technologies are being explored to optimize this stage of delivery. E-retailers are increasingly emphasizing last-mile fulfillment as they recognize its significance in gaining a competitive advantage in the e-commerce supply chain [38]. Efficient delivery management is challenging and requires detailed planning, especially for online orders with prompt home delivery. The final stage involves direct customer interaction, so delivery personnel need to be customer-centric and professional. According to Consoli [39], e-commerce customers prioritize time savings, cost-effectiveness, and a wide range of choices, including the ability to purchase products not available locally, compare prices, and benefit from doorstep delivery convenience. Meeting the demand for fast and on-demand delivery while controlling costs is challenging due to factors like inaccurate addresses, busy customer locations, driver shortages, economic fluctuations, unavailability of recipients, narrow delivery windows, high customer density, and environmental obstacles. Adoption of ADVs holds promise in improving last-mile deliveries by enhancing security, reducing delivery times, and contributing to cost savings and lower emissions in last-mile transportation. Integrating ADVs can help companies cut costs and improve customer satisfaction, despite initial implementation costs. However, widespread acceptance of ADVs is impeded by concerns about risk, lack of regulation, operational challenges, and the advanced nature of the technology.

2.3. Technology risks

When considering the adoption of ADVs, it is important to carefully assess the potential risks. Reliability of the technology, accessibility of fueling or recharging stations, and the vehicle's range are key factors to consider. The rise in ADVs could lead to congestion and security concerns, such as cyberattacks and unattended goods. Managing breakdowns without a driver and navigating obstacles are significant challenges. Recovery services may be needed for vehicles going to the wrong location or facing route obstructions. The introduction of ADVs will lead to job displacement but also create new roles for fleet managers and operators. Challenges include security, maintenance, and operational impediments. Costs involve technology, maintenance, and manual labor. Autonomous vehicles face challenges from obstructions and external factors.

2.4. Technology risk mitigation

ADVs rely on remote operators for unexpected situations, but level-five autonomous systems are needed for reliable last-mile delivery. These systems, though not yet deployable, require complementary technologies for success. Level-five autonomous vehicles can navigate mapped routes without human input and can safely transport passengers or goods once a destination is set. Despite current debates, level-five autonomy is not ready for public roads yet. The success of autonomous last-mile delivery relies on advanced cognitive capabilities for navigation, adaptation to unforeseen circumstances, and safe operation in urban environments [40]. At present, remote human operators are essential for automated vehicles involved in last-mile delivery services to respond to and manage dangerous situations. Companies are striving to minimize the remote-operator-to-fleet ratio and emphasize the need for driverless vehicles to achieve level five autonomous driving. Level five autonomous vehicles are expected to be revolutionary, boasting advanced self-configuration, self-healing capabilities, and the ability to foster social interaction between drivers and passengers. ADVs could mitigate congestion and infrastructure stress, resulting in quicker package deliveries and potentially reducing the number of vehicles on the roads. Effective route planning is vital for maximizing the efficiency of ADVs and involves considerations such as speed limits and the availability of fueling or battery-recharging stations. By refining their scheduling processes, logistics companies can decrease the number of vehicles on the road, thereby reducing traffic congestion and their overall environmental impact.

Despite facing challenges, AI holds tremendous potential in improving autonomous vehicles, analyzing large volumes of data, and addressing concerns related to last-mile delivery. AI can calculate the most efficient route, taking into account factors such as weather, traffic, and road conditions [41]. It can also work in tandem with other technologies. Kreuzer and Sirrenberg [41] observe that autonomous technology plays a crucial role in streamlining last-mile delivery operations, with different adaptations of autonomous technologies shaping last-mile delivery based on infrastructure, product offerings, population density, and customer preferences. Furthermore, AI can improve supply chain visibility by minimizing communication errors and streamlining distribution networks, thereby enhancing warehouse and transportation operations. AI technologies have proven to be invaluable for businesses in analyzing complex data sets. Major companies such as Walmart, Tesco, DHL, UPS, and FedEx utilize AI-powered route planning tools to optimize their delivery operations. DHL, for example, has implemented their "Greenplan" dynamic tour optimization tool to address the challenges of delivery complexity. Route optimization involves more than just finding the shortest path between points; it must consider variables like location, necessary stops, and delivery timeframes. By using AI-powered tools such as Greenplan, DHL was able to achieve a 20% reduction in delivery costs and computational time compared to traditional optimization techniques.

2.5. Legal risks

In order to integrate ADVs into urban infrastructure, it is crucial that they do not disrupt the flow of vehicles, cyclists, or pedestrians. Concerns about sidewalk ADVs in cities like New York, Los Angeles, and Toronto have led to proposed or enacted bans. Navigating varying laws and regulations presents a challenge for ADV companies, potentially complicating their business models and competitive advantage. Jennings and Figliozzi [34] highlight the difficulty of regulating ADVs in the United States, with regulations implemented in several states and cities. San Francisco, CA, has the strictest ADV legislation in the US, while Arizona's laws are the most lenient. Hoffmann and Prause [9] have pointed out legal concerns regarding the protection of personal data stored in ADVs, potentially violating the European General Data Protection Regulation (GDPR). Inconsistent government policies and lack of standardization are also highlighted as potential obstacles for the successful implementation of ADVs [42].

One of the main safety concerns associated with ADVs is the potential for increased congestion on streets and sidewalks, especially in urban areas. The interactions between ADVs, pedestrians, and other vehicles, whether autonomous or non-autonomous, can lead to significant traffic issues, causing delays and uncomfortable situations. When an ADV crosses an intersection, it can disrupt multiple traffic factors, impacting not only goods and transportation but also everyone involved. Companies deploying ADVs aim to maximize their benefits by minimizing the ratio of remote operators to fleet size, ideally reducing it to zero. Although ADVs may reduce road congestion, there is a possibility that congestion may be shifted to sidewalks, as suggested by Jennings and Figliozzi's [34] research on using sidewalk ADVs to alleviate congestion, potentially leading to unintended consequences.

Sidewalk ADVs have the potential to mitigate the increasing problems caused by heavy traffic in urban areas. However, deploying these vehicles on sidewalks could lead to other issues, such as pedestrian congestion and safety concerns. Despite this, Simoni et al. [25] propose that using sidewalk ADVs for last-mile deliveries could benefit customers in city centers, particularly where traffic congestion is most severe, based on the findings of their study.

2.6. Legal risk mitigation

In their 2020 publication, Sindi and Woodman [42] offer valuable insights on regulating ADVs, emphasizing the importance of standardization. Ostermeier et al. [33] recommend further research on ADVs' use in urban planning, like operational zones and speed limits, to evaluate regulations and ensure safe integration on roadways. Hoffmann and Prause [9] establish a regulatory framework for autonomous delivery robots for parcel transportation in 2018. The study focused on legal considerations and categorized mobile robots as cyber-physical systems for Industry 4.0, emphasizing their autonomous operation and efficient parcel delivery routes.

2.7. Public acceptance risks

One potential obstacle for ADVs is the public's reluctance to embrace them. This hesitation may arise from concerns about privacy, safety, and noise levels. According to Hoffmann and Prause [9], new technology often faces resistance before gaining widespread acceptance, which is consistent with the concept of cultural lag introduced by Ogburn [43]. As previously mentioned, ADVs may conform to this trend, particularly considering the necessity for standardized regulations. Additionally, accessibility is a factor in acceptance, as certain individuals may be unable to receive deliveries via ADVs due to disabilities or technical constraints.

2.8. Public acceptance risk mitigation

In a recent study, Schaudt and Clausen [35] emphasize the importance of addressing the growing demand for goods and meeting customer expectations. They suggested that using ADVs for timely deliveries could enhance customer satisfaction and lead to greater acceptance of this delivery method. Dynamic dispatching of ADVs to adapt to late orders and changing customer preferences throughout the day could offer additional benefits, such as reducing delivery costs and promoting societal acceptance. Customer acceptance of ADVs may take time to develop, given that this is a new and innovative technology [32]. Additionally, Pani et al. [44] find that 61% of customers, especially urban "e-shopping lovers" and "omnichannel consumers," were willing to pay extra for delivery via ADVs. One innovative concept involves a vehicle with multiple compartments, each containing packages for individual consumers. This vehicle is stationed outside major residential buildings, enabling residents to collect their packages as they enter the building. In buildings with a door attendant, the individual can intercept the autonomous vehicle at the curb and convey packages to the lobby or mailroom, providing a partial solution. Alternatively, several companies are designing robots specifically for door-to-door delivery. For instance, Agility Robotics has developed "Digit," a robot capable of walking and climbing stairs. In 2020, Ford Motor Company acquired digit prototypes to deploy lifelike robots from a delivery van to deliver packages directly to your doorstep [45]. Other delivery robots are currently in the development phase or undergoing testing.

2.9. Cost and security risks

The implementation of ADVs presents a challenge in modern societies due to security risks and high costs. However, investing in ADVs and hubs can result in significant benefits [34]. Nevertheless, the investment cost of a more extensive network of robot depots must be carefully evaluated in terms of delivery performance [27]. Moreover, security concerns arise from the potential theft of ADVs. Despite their considerable weight, entire units carrying valuable cargo can still be vulnerable to theft.

2.10. Cost and security risk mitigation

An effective way to minimize investment expenses and maximize benefits is to engage a third-party logistics service provider that employs ADVs. Given the substantial investment needed for IT support and hardware, many businesses choose to delegate their last-mile delivery to third-party logistics (3PL) companies. Wilding and Juriado [46] observe that this choice is typically influenced by cost and revenue considerations. E-commerce companies can circumvent substantial IT and hardware investment and operational costs by outsourcing to 3PL providers, as noted by Lacity and Hirschheim [47], who suggest that outsourcing can lead to cost reductions of 10–20%.

Security is paramount, requiring the installation of a secure goods compartment that is resistant to break-ins and can only be accessed with a customer-provided code. ADVs can be equipped with weight sensors, GPS, and cameras to oversee the cargo removal process [34]. Proper data-sharing protocols need to be in place to support urban planning while safeguarding the privacy of user and bystander data.

2.11. Drone delivery in the last mile

In the realm of last-mile delivery, aerial delivery drones have become a powerful presence, providing unmatched speed and efficiency. The sector is set to dominate the autonomous last-mile delivery market. Drones offer a wide array of benefits and have the potential to operate autonomously, significantly benefiting smart cities' package deliveries and reducing traffic congestion and transportation costs. Major industry players have already integrated drones into their delivery systems, with concerns about airspace management being raised. Although drones have the potential to surpass traditional delivery methods and access unrestricted routes, their use for parcel deliveries in urban areas is challenging due to safety and operational regulations [48]. Furthermore, their limited capacity and range [49] present additional constraints. The range of drones is affected by factors such as battery capacity, flight speed, and payload, as highlighted by Murray and Chu [50]. Complex multi-delivery operations are still beyond the capability of drones, prompting researchers to explore the integration of delivery trucks and drones [51]. In this system, the truck acts as a mobile charging station, replenishing the drone for its next flight. Drones are primarily used to serve customers in remote areas that are inaccessible by truck due to issues such as poor road conditions, high delivery costs, or extended delivery times. However, the limited operating time following a full recharge may prevent them from reaching certain locations or fulfilling all customer orders. In Guangam, Sichuan, JD Logistics has introduced drone delivery services in China.

These drones can handle 25% of the city's daily orders and reduce delivery times by up to 50%. They use the Y-3 model of UAVs, which can carry a maximum of 10 kg and fly up to 10 km from JD headquarters. However, due to the distance limitations, the drone cannot return to the truck for recharging during its flight. Therefore, a drone-truck recharging station is needed for delivery operations in rural Chinese villages under JD Logistics [52]. These are important considerations for the future of drone delivery in the last mile. Companies like Alibaba and Amazon have tested drone delivery for small packages. Amazon has shown the capability to deliver within half an hour of an order being placed.

2.12. Potential risks and mitigation strategies for drones

For drone delivery to become feasible, regulations need to be established for commercial use. Despite this, it is evident that delivery drones signify a new standard of excellence in technology and logistics for e-commerce enterprises and customers alike, with safety being a top priority.

2.13. Technical risks

The use of drone-based last-mile delivery may pose technical challenges such as risks from malicious codes, improper parameter configurations, and potential data breaches. Threats from external objects primarily concern physical harm to the drone and its payload, as well as compromising security and privacy. Extensive research has been focused on examining the potential risks associated with signal interference in the last-mile drone delivery process. It is crucial to be mindful of these threats and implement the required measures to guarantee secure and efficient drone delivery.

2.14. Technical risk mitigation

Technical solutions incorporate geo-fencing and no-fly zones to restrict access to specific areas, buildings, or infrastructure. These measures can be enforced through drone sound detection [53], built-in transponders, or software limitations [53]. One proposed solution involves equipping drones with chips to enhance accountability, as suggested by the Department for Transport in 2016. Additionally, there are suggestions to design quieter and more environmentally friendly drones, put forward by Kornatowski et al. [54] in 2018, respectively.

In order to protect their microcontrollers from potential code risks, recent research suggests that managers of drone systems should consider using input/output firewalls and fingerprint monitoring [55]. To protect the drone software from attacks, managers can use anti-malware programs, digital signatures, and obfuscation techniques. They can also monitor any suspicious I/O activities in the microcontroller memory using an I/O firewall and observe the processing activities within the microcontroller system using fingerprint monitoring. Additionally, supply chain managers should inspect third-party facilities to prevent backdoor malware during manufacturing. To protect drone application programming interfaces (APIs), system managers can use security measures like passwords, encryption, and anti-malware programs. Last-mile drone delivery relies on internet APIs for communication, making these security measures standard practices for API protection. Sensitive data within the drone should be encrypted, password-protected, and stored in secured, isolated locations. Ground control system managers can implement remote backup and attestation mechanisms for secure data storage. To mitigate risks associated with communication signals during last-mile drone delivery, various measures have been researched and proposed, such as securing and ensuring the reliability of GPS signals, broadening the usage of different frequencies and satellite networks to enhance GPS reception, and using encryption to protect camera signals from unauthorized interception or corruption.

Drones have traditionally been operated using remote control, but the integration of AI for automating their functions is becoming increasingly common [56]. Although drone models may vary, they all rely on a core operating system where engines drive each propeller. The engine power corresponds to the speed and lifting capacity of the drone. The speed control mechanism connects the battery to the motor and sends signals for energy release. The battery provides power, and the charger facilitates repeated usage. According to Appelbaum and Nehmer [56], the drone's GPS and camera are managed by its onboard computer, which also transmits data through the radio transmitter. With the assistance of its sensors, the drone can gather environmental data and integrate AI technology. Through autonomous flight, AI-powered drones can employ computer vision to detect and track objects and even modify their routes without human programming or intervention. These drones heavily rely on their sensors and data vision to navigate around obstacles and adapt to changing environmental conditions, as emphasized by Kim et al. [57]. It is crucial to utilize AI-powered platforms for identifying the most efficient transportation routes for robots and drones. These platforms collect and analyze real-time data, including ecological conditions, geography, traffic patterns, and delivery information, to optimize the navigation system of vehicles. This approach provides significant cost savings since robots do not require salaries and operate continuously without the need for breaks [35]. Recently, proposed airworthiness criteria have been introduced for the type certification of delivery drones to facilitate commercial operations. These unmanned aerial vehicles transport a variety of goods, such as medical supplies, packaged items, and food. Typically, delivery drones operate autonomously. For instance, Amazon has successfully tested drone deliveries and achieved a 30-minute delivery time. To gain a competitive advantage and enhance delivery services, many modern businesses aim to reduce delivery times. AI-powered concepts, such as self-driving delivery robots and drones, are replacing traditional business models, diminishing the necessity for human involvement in the delivery process. Technological progress is moving from transactional to cognitive automation, primarily utilizing AI for business decision-making. Autonomous drones help mitigate labor costs and eliminate human errors, such as negligence, disorientation, and incorrect recipient delivery [58]. Particularly in urban areas, drones are highly effective in reducing labor costs and delivery times because they operate autonomously [58].

2.15. Legal risks

The ongoing discussion on commercial drones often focuses on the challenges of strict regulation and lack of legal consistency. One major hurdle for the drone industry is regulation, as technological advancements are outpacing regulatory development. This contrast highlights the cautious approach of the aviation industry, which contrasts with the rapid pace of innovation. The FAA's careful regulations have contributed to the US maintaining one of the world's safest airspaces, with a focus on preventing unregulated drone flights that endanger lives and critical infrastructure. Ensuring safe coexistence of drones and airplanes, averting midair collisions, and reducing ground risks are the agency's top priorities.

2.16. Legal risk mitigation

Various strategies have been suggested to address legal issues related to drone use, including mandatory drone registration, code of conduct enforcement, and the expansion of regulatory frameworks to protect privacy rights. The goal is to establish a comprehensive regulatory structure governing drone operations and data collection, ensuring the protection of individuals' privacy rights. This involves eliminating or masking irrelevant personal data and implementing measures to prevent unauthorized storage and dissemination of personal data.

The potential for flying drones beyond the visual line of sight (BVLOS) is a game-changing opportunity for commercial drone operators. However, currently, obtaining a special waiver from the Federal Aviation Administration (FAA) is necessary to fly BVLOS in U.S. airspace, a challenging and time-consuming process. To fully realize the potential of drone deliveries, it is crucial that more unmanned aircraft receive Part 135 certification from the FAA. Wing, as a pioneer in obtaining this certification, has enabled BVLOS deliveries and opened up possibilities for other drone delivery companies. Despite the slow progress, those in the drone delivery industry recognize the numerous advantages it offers once scaled up.

2.17. Public acceptance risks

An important set of anticipated risks pertains to the public's hesitance to embrace drones. Concerns about privacy violations, safety, and noise levels contribute to this resistance. The theme of acceptance features prominently in literature discussing the implementation of commercial drones. Multiple researchers studying this topic concur that the adverse effects of widespread drone usage will primarily affect urban populations [59, 60]. Considering the potential negative repercussions, it is essential to assess how these may impact public acceptance.

Instances of mid-air collisions, crashes, and malfunctions are major concerns in urban areas. Misuse of drones by criminals or terrorists poses a significant threat, including smuggling, hacking, and privacy violations. Terrorist exploitation of drones includes weaponization, targeted payload drops, and disruption of GPS signals. Drones' surveillance capabilities raise privacy concerns due to their ability to capture digital documentation, potentially compromising personal privacy and intruding on private spaces. Drones' silent and high-flying nature makes them difficult to detect. Integrating sensing and surveillance technologies is crucial for transportation drones to avoid collisions and ensure a smooth delivery process. However, using delivery drones in close proximity to private areas may lead to unintentional or intentional privacy violations.

2.18. Public acceptance risk mitigation

There are a variety of strategies that can be employed to reduce the risk of privacy violations caused by delivery drones. One of the most popular technical solutions is the implementation of remote identification systems directly within the drones themselves. In addition, experts recommend that drone designs incorporate preventive measures, such as privacy impact assessments in real-time using special algorithms and software designs. This approach, known as privacy by design or privacy by default, has been discussed by several researchers [58, 61]. Additionally, some experts advocate for participatory methods to increase public acceptance. By engaging in public consultation processes, a shared understanding of the future use of urban airspace can be achieved. Various technical methods are available to prevent privacy violations, including geofencing and no-fly zones. As an example of different approaches to this issue, Wang et al. [62] suggest a programmatic approach that involves making both drones and their controllers more visible and responsible, promoting communication between drone operators and the public, and designing drones with consideration for local social and cultural norms.

Potential solutions are designed to mitigate the potential harm caused by drones, either through damage reduction or prevention. One promising approach involves establishing universal registration protocols for operational drones, which would offer greater clarity about liability in the event of an incident.

2.19. Economic risks

The incorporation of drones into urban areas poses anticipated infrastructural risks that require careful consideration. Two crucial areas of potential planning and infrastructural issues have been identified. First, there is a need for urban planning processes to be developed, as local planning authorities may not be prepared to integrate a new dimension of mobility into existing planning practices [63]. Additionally, it is important to establish an enabling planning practice and reconcile conflicting interests. There is a growing demand for participatory planning practices [64]. In addition, there is a pressing need to enhance the clearly defined requirements for physical infrastructure [64].

2.20. Economic risk mitigation

The strategic placement of charging and depot facilities plays a crucial role in determining the most efficient delivery routes for urban air logistics. This consideration has a significant impact on sustainability, effectiveness, and profitability [50, 63–65]. Scholars emphasize the importance of addressing operational needs when deploying drones, including the expansion of infrastructure for parking, storage, and charging [63, 66]. For private sector companies operating in urban air mobility, a well-connected hub infrastructure is seen as an essential element of their business model.

The creation of new infrastructure could provide a potential solution, and the establishment of networks of small distribution hubs could facilitate the last-mile delivery by drone [65, 67]. While delivering to suburban areas is feasible [68], there is a lack of recommendations for dense urban areas. Nevertheless, repurposing local parcel delivery stations could offer a viable option (see Table 2).

3. Discussion

The autonomous last-mile delivery market is shaped by various factors, including the growing demand for efficient delivery services driven by the expansion of e-commerce. Among the challenges are regulatory gaps and safety concerns. Nevertheless, autonomous technologies bring about advantages such as cost reduction, enhanced speed, and environmental solutions. The adoption of these technologies faces hindrances related to regulations, technical requirements, and financial barriers. The integration of new technology allows for real-time data exchange and seamless communication. Digital service systems provide immediate access to information, potentially raising consumer expectations. The implementation of IoT and cloud computing technology offers benefits such as real-time tracking and route optimization. Intelligent transportation systems can adjust routes and schedules to prevent congestion. Loading-bay booking systems and public infrastructure upgrades enable real-time interaction between vehicles and infrastructure for efficient allocation of loading and unloading space.

Table 2
Risks associated with ADVs and drones and mitigation strategies

ADV/Drone risks	Mitigation strategy
Lack of Regulation	Consistently evaluating regulations is fundamental to ensuring the safe integration of different modes of transportation, including roadways and airspace. This ongoing process involves carefully assessing and updating regulations to account for evolving technologies, traffic patterns, and safety standards. By continuously evaluating regulations, harmonious and secure transportation environment for all road and air users can be created. It is crucial to establish and implement comprehensive policies and regulations that effectively align incentives and clearly define expectations for the autonomous delivery vehicle (ADV) industry. Taking action now is essential to ensure that these standards are in place before the industry's operations become deeply rooted.
Operational Challenges	Outsourcing to third-party logistics (3PL) providers is a strategic business decision that involves contracting out logistics and supply chain management functions to specialized companies. Outsourcing to 3PL providers can also help businesses reduce operational costs, enhance scalability, and gain access to advanced technology and industry best practices. Keep in mind that it is important to comprehend the initial cash outlays as they will play a key role in generating a favorable return on investment (ROI) in the long run.
Advanced Nature of the Technology	Utilize the latest advancements in learning AI and machine learning tools in order to stay updated on cutting-edge digital enhancement technologies.
Obstructions	AI-powered tools utilize advanced features such as auto-sensing and recovery technology to enhance performance and ensure seamless operations.
Data Security	Urban planning relies on the availability of data, but it is crucial to establish data sharing protocols that not only ensure the accessibility of information but also safeguard the privacy of both users and bystanders.

Cutting-edge autonomous drones and robots powered by AI technology offer a cost-effective and environmentally friendly solution for last-mile delivery. These advanced technologies provide real-time delivery solutions, improve safety, and enable live delivery tracking. AI in the delivery industry also plays a crucial role in analyzing traffic patterns and improving transportation reliability, ultimately leading to increased productivity and reduced labor costs. Integrating drones and sidewalk robots into last-mile delivery systems offers compelling benefits for business, including improved operational efficiency, lower costs, enhanced environmental sustainability, and an improved customer experience.

There are inherent risks associated with the deployment of ADVs. Acceptance and trust are two major risks that need to be addressed and overcome. For ADV's to be successful, the general public must accept them as regular fixtures in everyday life, and trust that they will perform as advertised. Specific risks include safety (pedestrian and property), cybersecurity and the resilience of operating systems, potential employment losses in the transportation and delivery industries due to ADV's, and fire hazards due to lithium-ion batteries. To mitigate these risks, strategies can be employed, such as building public trust through transparent testing and deployment, safeguarding the privacy of drivers, passengers, and third parties, protecting against cyberattacks through encryption and authentication, considering additional responsibilities for ADV owners/operators with regard to the vehicle's activities, and documenting and communicating roles and responsibilities for monitoring risks, including fire hazards. ADVs have the potential to revolutionize last-mile delivery by boosting efficiency, reducing costs, and improving safety. However, successful implementation requires addressing technical, legal, and public acceptance challenges.

4. Conclusion

The integration of ADVs and drones is still in its early stages. Further research and development are required before these technologies can be utilized on a larger scale. Moreover, integrating these technologies into existing last-mile logistics and delivery infrastructure poses challenges, including the establishment of new regulations, implementation of new logistics management software, and integration into current delivery networks. The demand for rapid and efficient delivery services driven by the swift expansion of e-commerce is a major factor influencing the autonomous last-mile delivery market. Additionally, the need for secure and contactless delivery methods is propelling the adoption of autonomous solutions.

Challenges to autonomous last-mile delivery include regulatory gaps, safety concerns, cutting-edge technology, and operational obstacles. The regulatory landscape presents a significant obstacle, with gaps in current transportation norms and policies leading to safety concerns. The emphasis on the necessity for fail-safe systems to prevent accidents and foster public confidence has emerged. Cutting-edge technologies have the potential to revolutionize last-mile logistics and delivery but are costly. Operational impediments, such as high implementation costs, traditional traffic management that hinders ADVs, and infrastructure pitfalls, must be overcome. The potential for ADVs and drones to bolster efficiency, cut costs, and enhance safety represents an exciting and rapidly evolving field in last-mile logistics and delivery.

Ethical Statement

This study does not contain any studies with human or animal subjects performed by any of the authors.

Conflicts of Interest

The authors declare that they have no conflicts of interest to this work.

Data Availability Statement

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

Author Contribution Statement

James E. Zemanek Jr.: Conceptualization, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration. **John F. Kros:** Conceptualization, Validation, Writing – review & editing.

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