Zero Emission Freight Transport and Impact on Last Mile Delivery

Samuel Babjak & Chris Yung, Bachelors of Science, Aalto University; School of Engineering; Department of Built Environment

Abstract

This literature review explores mainly the challenges and potential solutions in urban freight transportation, for last-mile logistics. The growing number of delivery vehicles in urban areas has led to problems such as traffic congestion, competition for parking spaces, noise, and air pollution. To address these issues, the paper focuses on the last mile problem in transportation logistics and the potential of disruptive innovations, a potential of disruptive innovations such as Unmanned Aerial Vehicles (UAVs) and Autonomous Delivery Robots (ADRs) as alternatives to traditional Internal Combustion Engine (ICE) vehicles. It highlights the drastic operational differences between aerial drones and ADRs and the need for changes in operational procedures to fully leverage these technologies. The study also discusses routing strategies and delivery routes, emphasizing the shift from one-route delivery to a point-to-point model with the advent of autonomous vehicle technologies. The paper concludes that while these technologies can reduce costs and emissions, their effectiveness depends on the specific urban setting and operational factors.

1.Introduction

The rise of eCommerce, increase urbanization, and demographic growth have created an increased demand for urban freight transportation. The COVID-19 pandemic has accelerated the increase of eCommerce as shops closed and the reduction of contracts was warranted due to government restrictions and the increase is projected to continue. According to the Pitney Bowes Parcel Shipping Index, parcel sipping per capita has grown from 12 parcels per person in 2014 to 34 parcels per person in 2020 and is estimated to double in the next five years. (Pitney Bowes, 2022) To meet this demand, logistic companies will need to employ more delivery vehicles to meet existing and future demands to deliver parcels to increasingly larger urban areas.

However, the growing number of delivery vehicles within urban areas can result in numerous problems, traffic congestion, competition with parking spaces and public spaces, noise, and air pollution are some of the externalities induced by the growing numbers of delivery vehicles. Economics, environment, and social, the three pillars of sustainability are linked to urban logistics. Within the economics side, the last mile problem is often the least efficient in terms of costs, and shipping cost is linked to the price of the good, and minimizing cost is one priority of an efficient logistic system. In the realm of the environment, heavy vehicles disproportionally contribute to air pollutants and emissions in terms of per-vehicle emissions. With high logistics demand, tailpipe emissions from delivery vehicles pollute within city boundaries directly exposing residents to air pollutants and negatively affecting their health and social well-being. In addition, the EU has set climate goals of a reduction of at least 60% GHGs by 2030 concerning 1990 levels. Therefore, there is a consensus to increase the sustainability of urban logistics while accommodating future growth.

One method to reduce the impact of urban logistics is to utilize and replace traditional delivery methods with greener modes of delivery. Within this paper, a focus will be researching the last mile problem in transportation logistics and the use of potentially disruptive innovations that can disrupt the traditional internal combustion engine (ICE) technologies currently employed by existing freight companies. The method of evaluation, certain advantages, and disadvantages of the disruptive technologies over existing ICE will be explored.

2. Literature review

According to the article, Smart urban logistics: Literature Review and future directions, cities must become' smart' to overcome the challenge of limited resources in the urban environment. Integrating emerging technologies such as machine learning, artificial intelligence, and/or big data analysis into the urban fabric is required to become a 'smart' city. Therefore, we choose to focus on emerging, "smart" urban logistics to cope with the challenge of increasing urban freight demand. (Gülçin Büyük¨ozkan, 2022).

The literature review breaks the search of relevant articles into distinct phases, keywords that are related to urban logistics (i.e., Last Miles Logistics, Urban Goods, City Logistics, etc.) and Smartness Related (i.e., Autonomous Vehicles, Drones, Robotics, Block Chain, etc.). The research article examined must state both an urban logistic and smartness keyword within its abstract or title to be included within the literature review. The article must also be published between the years 2000 – 2020. A total of 71 articles and 59 conference papers were filtered and examined by the authors. Each is further classified under main topics and applications and discussed technologies and smart solutions.

The authors found that a total of 17 main topics and applications, which discuss which topic is being covered within the realm of urban freight transport, emerged. The top 3 topics that were discussed are last-mile delivery, vehicle routing problem, and solutions assessment and comparison. The author noted and we can confirm that many of the papers listed cover more than one topic and it was difficult to categorize each one as its distinct category. The author of the review categorizes them based on the most frequently mentioned issue. However, we didn't feel it was correct to categorize each article into one category as urban logistics has many different distinct pieces that work together to deliver goods. For example, the article we review, Potentialities of drones and ground autonomous delivery devices for last-mile logistics, covered the topic of last-mile delivery, placement of Urban Consolidation Centres (UCCs), optimization of vehicle routing, and solution assessment and comparison of technology. A comparison will not be relevant if it fails to consider all the relevant parts. Therefore, we concluded the term last mile delivery is an umbrella term that covers most urban logistic requirements and operations.

Within technologies and smart solutions, the articles reviewed are more clear-cut than their topics and applications. 15 solutions were categorized by the authors and the top 3 topics were unmanned aerial vehicles, intelligent transportation systems (ITS), and GPS/GIS technology. Upon review of ITS, the topic is broad and can include studies related to traffic information systems, vehicle networks, and commercial vehicle operations. We have decided not to include ITS within our paper as it eclipses multiple different technologies. Reviewing GPS/GIS technology mostly pertains to the real time tracking of products and goods. As this technology focuses on the good and does not directly affect cities, it was decided that this technology will not be reviewed. Looking at the next highest ranked technologies, Autonomous Vehicles and Electric Vehicles/Cargo Bikes for fourth and fifth ranked respectively, we observed there were more articles within autonomous vehicles than electric vehicles/cargo bikes. In addition, unmanned aerial vehicles can be both remote-controlled and autonomous. We, therefore, decided to research unmanned aerial vehicles and autonomous vehicles as they both can be grouped with new modes of autonomous transportation.

3. Technology Description

The following section describes traditional delivery vehicles and introduces UAVs and ADRs, with a brief description of their characteristics, limitations, and use cases.

3.1 Traditional Delivery Vehicles Characteristics

Within the European Union, which follows the United Nations Economic Commission for Europe classification of vehicles defined as any power-driven vehicles having at least four-wheel and used for the carriage of goods fits within the category N. The smallest category of said vehicles category is N1 which is defined as "motor vehicles used for the carriage of goods having a maximum mass not exceeding 3.5 tonnes" (Economic and Social Council UN, 2005). These vehicles are shorter than heavier freight transportation which makes them ideal for urban logistics and last-mile delivery. Currently, these vehicles are powered by internal combustion engines (ICE) but industry trends are pushing for the electrification of these vehicles. Most articles, if considering the incorporation of the electrification of delivery vans, assumed even with the electrification of the fleet, operational behaviour would not change. It is assumed there will be a significant range and capacity compared to traditional ICE-powered vehicles.

3.2 Drones / UAVs Characteristics

The enhancement and capability of individual processes and the capacity of the system can be achieved in multiple ways, with remote technology and automation being among the most prominent. Historically UAVs have seen use as military vehicles, but their versatility allows them to transform logistics services (Joshuah K. Stolaroff, 2018). They can fly packages from a retailer's warehouse to the customer, providing point-to-point deliveries. Drones are quicker, more responsive, and faster to steer as they are not affected by congestion and can fly over buildings in a straight line. Drone delivery options include direct flights from the retailer's storeroom to the shopper, cargo transport by multiple drones via so-called waypoint stations, or UAVs carrying packages from a truck to the consumer and returning while the truck moves around delivery sites (Joshuah K. Stolaroff, 2018). However, they usually deliver one parcel on a round-trip (Clement Lemardel´ea, 2021). Various sensors are installed inside these vehicles for detection and guidance to improve and optimize the efficiency of parcel delivery (Gülçin Büyük¨ozkan, 2022)

Aerial drones, powered exclusively by batteries, have similar characteristics to ADRs (Clément Lemardel´ea., 2021). Electric-powered drones' specifications are less clear than ADRs due to their developing technology and limited applications. Characteristics assumed in Lemardel´e et al.'s modelling exercise include travelling speeds of 80 km/h, landing and take-off speeds of 30 km/h, and a storage volume of 2 cubic meters. The range is highly uncertain, as it depends on numerous factors, such as battery chemistry, battery mass, payload, weather conditions, flight altitude, aerial dynamics of the drone (Quadcopter or Octocopter), acceleration frequency, and safety buffer. Theoretical maximum ranges of 5 km and 8 km for existing and future battery technology for quadcopters were calculated (Stolaroff, 2018). However, these numbers do not consider package weight or take-off and drop-off, which will decrease the range. A key advantage of drones over ADRs is the ability to swap batteries between trips, allowing constant operation, whereas ADRs have integrated batteries (Clément Lemardel´ea., 2021).

Small, electric battery-operated UAVs can be more efficient than the fossil-fueled vehicles they replace (Joshuah K. Stolaroff, 2018). During the COVID-19 crisis, drones were used to deliver face masks to remote islands in Korea and treatment pills and medicines from pharmacies to retirement villages in Florida (Rico Merkert, 2020). In remote African areas, drones have been used for medical supply deliveries, which could preview their role in an urban parcel or small package delivery. In commercial applications, drones have reduced costs and enhanced capabilities in industries like mining, logistics, engineering, transport network management, and agricultural scanning (Rico Merkert, 2020). Several companies, including Amazon, Google, UPS, and Deutsche Post DHL, are developing commercial package delivery using drones (Joshuah K. Stolaroff, 2018). However, potential issues include congestion, traffic management safety, privacy and security concerns, and implementation in urban areas.

3.3 Autonomous Delivery Robots Characteristics

Autonomous delivery robots (ADRs) or automated micro-vehicles (AMVs) (Strubelt, 2019), sometimes referred to as Ground Autonomous Delivery Devices (GADDs) or Ground Autonomous Vehicles (GAVs) (Clément Lemardel ́ea., 2021), are electric-powered, motorized, self-driving (with automation levels 3 and 4) vehicles designed to deliver items or packages without human intervention. ADRs fall under the European vehicle category L (2-4 wheels, up to 45 km/h speed, and 400 kg tare weight) and can be monitored or remote-controlled by people without a driving license. Two types exist - Sidewalk Autonomous Delivery Robots (SADRs) and Road Autonomous Delivery Robots (RADRs). These robots can deliver several parcels in one tour, optimizing route length and reducing operation costs despite potential congestion or reduced speed (Clément Lemardel ́ea., 2021), having a vast range of operational characteristics due to their different development stages. ADRs are typically found in retailers-to customers' home settings, such as food delivery services (Doordash and UberEATS) and grocery delivery services (Instacart), which have seen a rise in popularity over the years. Within these markets, ADRs are used for delivering groceries, prepared meals, or medication from retailers or restaurants directly to customers' doorsteps. Domino's Pizza has partnered with Skydrop to test delivery of its pizza from the local Domino's store to the customer's home in New Zealand. While one for-one routes are more efficient using autonomous vehicle technologies than traditional delivery methods (Figliozzi M. A., 2018), it is unclear if the arrival of the delivery service induced an increase in orders. A review of these routing strategies was not covered in the cited studies.

Most ADRs use LIDAR as their primary means of sense, while some use cameras, computer vision, artificial neuronal networks, and LASERs for obstacle detection. Many ADRs are equipped with microphones and speakers for communication with people, and most use GPS for localization, often combined with other sensors and map services for better accuracy. Most ADRs feature communication technology such as WiFi or 4G, enabling remote control from a control centre, which enhances security and enables economic operation, as a single supervisor can manage 50-100 delivery robots without human assistance (Strubelt, 2019)

3.3.1 Main Types of ADRs

SADRs are pedestrian-sized robots that use sidewalks or pedestrian paths. They are relatively slow and lightweight, often limited by city and state regulations. Companies like Starship Technologies, Robby, and KiwiBot are prominent names in the SADR space (Rico Merkert, 2020). ADRs operating on sidewalks typically have a speed of 5 kph and a capacity of up to 100 kg depending on the type (Engesser, Rombaut, Vanhaverbeke, & Lebeau, 2023), but popular models like Starship can only carry up to 10kg, with a range of around 20 km but can be artificially limited by operators (Baum, Assmann, & Strubelt, 2019). In comparison to a van, the capacity of the vehicle is limited, so more vehicles need to be dispatched to yield the same maximum capacity. However, ADRs are more flexible as the number of dispatches can be adjusted to the daily fluctuation of parcel levels.

RADRs travel on roadways shared with conventional motorized vehicles. Designs like NURO are smaller and lighter than typical delivery vehicles, while others like uDelv and AutoX are based on existing vehicles that have been automated or modified for autonomous deliveries. RADRs can be accompanied by specialized "mothership" vans, which can drop off and pick up several RADRs for delivery (Figliozzi & Jenningsa, 2020). Operating on roads and away from sidewalks typically has higher speeds and capacities than SADRs. However, they are less developed, with only three operational AMVs out of 39 GAVs examined (Figliozzi & Jenningsa, 2020). Nuro, a true AMV, had a capacity of 113.4 kg a speed of 40 kph, and a range of 16 km. These ADRs operate closely to traditional vans as they are built to operate along routes with multiple stops. However, as range and capacity increase, so do battery size and vehicle weight, potentially disqualifying them as ADRs due to weight.

4. Different Approaches for UAVs and ADRs Assessment

Comparison of technology only includes ADRs, aerial drones, and traditional trucks to help determine which mode is better. A focus on economics, emissions, and energy use will help pinpoint the advantages and disadvantages of each technology. Emissions and energy use are combined as ICE trucks are typically used as a baseline unless otherwise stated. However, the inclusion of electric trucks will shift emissions to the grid, and a comparison of energy use is warranted.

4.1 Optimization and Scheduling

4.1.1 Routing Strategies

The operation of either aerial drones or ADRs is drastically different between the two as one operates on a three-dimensional plane while the latter operates on two dimensions. Compared to traditional urban logistics where a human drives from a distribution centre on a small diesel truck and deliveries multiple packages along a particular route, it has even further differentiation. (Lemardel´e, Estrada, Pages, & Bachofner, 2021) Different speeds, capacities, and ranges further change operational requirements and not to mention the autonomous nature of the two new technologies creating differences in economic costs. Expecting either technology to compete or even fully replace the existing technology without changes to the operational procedure will result in a futile attempt. Within this section, an explanation of differences in routing, technical characteristics, and their impact will be examined.

4.1.2 Delivery Routes

The emerging autonomous vehicle technologies within transportation logistics are emerging to compete with the traditional methodology of one-route delivery to a point-to-point model. The routing of packages should also adapt to this technology to optimize their costs to fairly compete with traditional delivery routes.

4.1.3 Traditional Delivery Route

A typical route for a courier delivering packages would start from a distribution centre (DC) where the packages would be assigned and loaded to a particular route. Trucks will drive to a particular service area which will then make multiple stops for delivery and return to the DC. Sometimes, if the option is available, parcel lockers are available, and some deliveries are routed to those lockers for customer pick up at a later point. This option decreases the distance travelled instead of traveling to all customer locations, the carrier travels to the lockers and delivers multiple parcels at once. An example of a traditional route can be seen in Figure 1a. (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

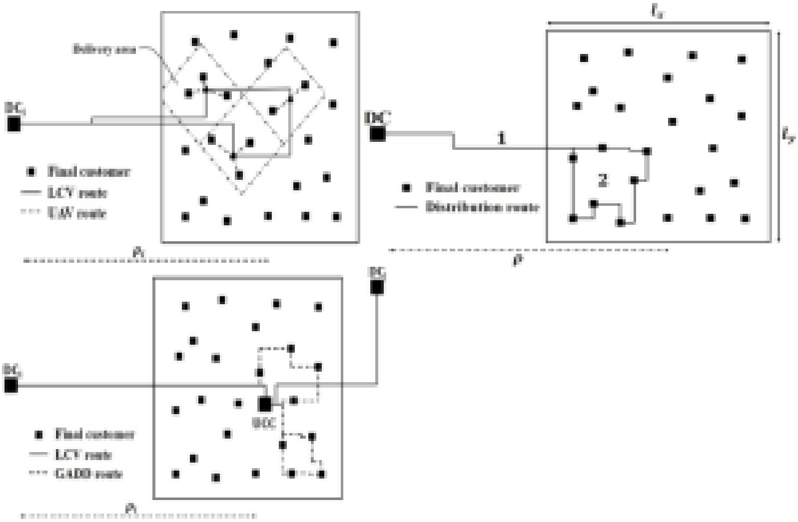


Figure 1: Various Delivery Routes a) Traditional Route, b) GAVs + UCC, c) Drone + Van (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

4.1.4 GAVs Delivery Route

Typically, DC is located far from residential centers and exclusive use of autonomous vehicles delivery cannot fully replace couriers due to its limited range. A method to overcome the range limitation is to create urban consolidation centres (UCCs) within the city and use the ADRs as the last mile delivery as shown in Figure 1b. A traditional truck would drive from the DC to the UCC and offload parcels. Workers within the UCC will deconsolidate the package and place each delivery within the ADRs which would then be sent out to the customer. The UCC will store, charge, and maintain the ADRs. It is unknown if each competing carrier will co-manage the

UCCs and ADRs together or will have competing networks. There are strong economic incentives to work collaboratively to achieve economies of scale as last-mile deliveries are common to all couriers. (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

Another method to increase the range is the use of "mothership", specialized vans to drop off and pick up several ADRs at once. Parcels are assigned a route within the DC and placed in mothership and driven to some service area. There, the mothership will offload ADRs to complete multiple last mile deliveries and return to the mothership. Multiple stops by the mothership can be made to reduce operational costs. Charging of the ADRs by the mothership (wherever from the van's battery pack or ICE) is a possibility to increase the number of deliveries. However, as the mothership must carry ADRs and battery packs, the space within the van dedicated to parcels will decrease. Trade-offs between the number of ADRs against the additional parcels will need to be considered. (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

ADRs also can serve multiple customers on each trip if the model selected has significant capacity and compartments. Generally, these are more limited to AMVs as they are designed to conduct multiple stops but ADRs can in theory be coupled. Within this paper, it is assumed ADRs can only serve one customer per trip. (Engesser, Rombaut, Vanhaverbeke, & Lebeau, 2023)

4.1.5 Aerial Drones Delivery Routes

Like ADRs, drones can operate in UCC or using motherships. Figure 1c for ex (Engesser, Rombaut, Vanhaverbeke, & Lebeau, 2023) ample, shows how the "mothership' concept works to deploy aerial drones. Drones require significant clearance such as a front yard to drop off parcels. It is unclear how the drone will be able to operate in dense urban environments. Would drones deliver parcels to rooftops, balconies, or the front door? These conditions remain unsolved. (Lemardel´e, Estrada, Pages, & Bachofner, 2021)

4.2 Acceptance of Technology

Adaption of the ADRs and aerial drones varied greatly with ADRs being able to penetrate many delivery markets with success. We assumed that ADRs are generally accepted by the public due to their popularity and clear definition as defined within the EU. This is not the case for aerial drones as there are few applications**.** In a study conducted by (Schaarschmidt, Bertram, & Knobloch, 2021), they survey participants about their concerns and find barriers to the adoption of drone deliveries. Of the participants of the surveys, there was a clear consensus of physical (chance of injury), financial (cost of delivery), and data/privacy risks (giving up personal information) as barriers to the adoption of drone technology. We have not reviewed physical and privacy risks within this report, but the papers reviewed show a potential reduction of operational cost as will be discussed in Section 5.4. The study concludes to increase the adoption of drone technology, all three risk perceptions need to be addressed to enhance the perception of drone technology's usefulness in the application of logistics.

4.3 Sustainability, lifecycle assessment- Emissions and Energy Usage

ADRs show significant reductions in emissions and energy consumption in urban areas, while UAVs demonstrate greater efficiency in specific scenarios. Both technologies depend on the urban setting and parcel density, with each technology potentially reducing costs and outperforming traditional delivery methods in specific scenarios. However, the superiority of either technology over the other remains unclear, as both cost and energy efficiency is influenced by operational factors and assumptions.

4.3.1 ADRs Lifecycle Assessment:

The study by (Cl ́ement Lemardel ́ea, 2021) calculated whether ADRs have the potential to be utilized in two European cities, specifically Barcelona's historical centre and Paris suburbs. They chose 4 different strategies to assess the potential use case, accounting for externalities associated with vehicles, including WTT (well-to-tank) and TTW (tank-to-wheel) emissions (mostly fumes and GHG), vehicle production externalities (only GHG from battery production), and the impact on urban infrastructure. The paper neglects end-of-life treatment externalities, which account for less than 5% of total externalities, as well as congestion, noise, and safety issues. They assumed the energy consumption rate of 0.03 kWh/km, WTT efficiency rate of 0.7, range to be 100km, and speed of 5km/h for ADRs. The results show that ADRs generate the lowest number of externalities, reducing emissions by 60% to 80% compared to the traditional, standard practise Strategy A0 with the widespread adoption of combustion engine delivery vans. Truck-launched delivery drones achieve around a 55% reduction in externalities, while Strategy A1 (where drivers do not transport the packages to the final clients but drop them in distribution bays, that concentrate the demand of an entire neighbourhood) offers a 20% reduction to ICE vans or 40% with EVs. They also conclude that in the Paris suburb use case, externalities decrease by roughly 70% compared to traditional delivery methods, given a demand density of 100 parcels/km2. In the Barcelona historical centre, using GADDs can reduce externalities by nearly 80% compared to conventional methods, with a demand density of about 300 parcels/km2.

Miguel Figliozzia, 2020 concludes that ADRs have the potential to reduce last-mile travel, energy consumption, and CO2 emissions compared to conventional delivery methods. This case study quantified the energy needed to deliver to 48 customers using various vehicle types. It was found that the energy consumption of eight SADRs is a small fraction of the energy consumption of the mothership van. In high-density urban areas with heavy traffic and limited parking, the small NURO vehicle may be the most efficient option. ADRs several times (although the study doesn't specify by how much) are more energy-efficient than conventional diesel vans and drones but have similar energy efficiency as electric vans like the Renault Kangoo. In terms of safety, the NURO is slower, smaller, and lighter than conventional vans, reducing the likelihood of severe crashes with pedestrians or cyclists. The adoption of smaller, driverless, and more economical ADRs could lead to higher utilization of electric commercial vehicles in urban areas, concludes the study.

4.3.2 UAVs Lifecycle Assessment:

A detailed review by Figliozzi assesses the potential effectiveness of drones to lower CO2e lifecycle emissions, comparing them to alternatives on the market. A similar study by Goodchild and Toy 2017 concluded that drones emit less than conventional substitutes, only when businesses are located close to the depot, suggesting that EV trucks and drones should complement each other. When CO2e was analysed, the authors considered the emission generation to charge the battery, as well as a battery to propeller emissions, and an analogous approach for conventional vehicles. They concluded that energy consumption for a drone MD4-3000 was 21.6 Wh/km compared to 1016 Wh/km ICE RAM Promaster 2500 pick-up truck. When assuming a payload of 5 kg the drone proved to be 47 times more efficient (energy consumed per unit distance), with the same energy consumed when the pickup travels one time delivering 47 packages. The overall efficiency of the drone (to deliver power to the battery and consequently to the propellers) is assumed to be 67% while in the case of an ICE truck is 25%. The emissions produced by the UAV are 22 times cleaner than the van on a per unit energy consumed basis. Taking into account the difference in the payload as a van can carry 378 times more cargo than one UAV trip, emissions produced by the UAVs are still 2.8 times cleaner even though at consumed 8 times more energy than the ICE truck.

Completely different results are achieved when drone emissions per delivery with the vehicle phase are calculated. The vehicle phase includes the emission produced as a result of manufacturing and disposal of the said drone itself and its batteries. Considering the emissions per unit of payload mass in the vehicle phase, UAVs produced 70 kg CO2e per kg compared to 5 kg CO2e per kg for the diesel van. Electric trucks and vans are more efficient than typical US vans, making UAVs less efficient than electric vans for delivery scenarios with over 10 customers per route (Figliozzi M. A., 2018).

In a study by Kirschstein, 2020, energy utilization models were employed to evaluate the energy requirements of UAVs, EV trucks, and traditional pick-ups for distributing packages to clients from a central distribution centre. The corresponding CO2e emissions were calculated and compared based on energy needs. Under low and moderate traffic congestion, diesel trucks necessitate approximately 40-50% more energy than EVs and 80-90% more energy in situations with high congestion.UAVs often require more energy than diesel trucks in most situations with medium wind conditions. In very specific cases such as a low number of customers per stop, low to moderate wind speeds, medium traffic congestion, and a customer area radius of 8km, UAVs consume less energy compared to EVs. Kirschsetistein`s study also concluded that UAVs, in many scenarios show no environmental benefit over the use of diesel vehicles, as UAVs emit less CO2 only if the CO2 emission coefficient is lesser than 0.3 kg CO2e/kWh in rural situations, having an 8 km customer area of coverage and 2 destinations per stop. What needs to be noted though is this was a theoretical study in contrast to the real-world case of the Goodchild and Toy, 2017 study.

Another study by Joshuah K. Stolaroff, 2018 in a real-world test found test standard configuration was not advised for package delivery at longer ranges; however, increasing battery size can increase range, with a maximum range of around 5 km for both quadcopter and octocopter. With a chosen battery sizes of 1 kg for quadcopter (range of about 3.5 km) and 10 kg for octocopter (range of about 4.2 km) and an average energy density of 150 Wh/kg study pointed out the necessity of additional warehouses close to customers, increasing energy use. Based on calculations a small quadrotor drone (delivery of 0.5 kg package) has lower impacts than diesel truck delivery, ranging from a 54% GHG reduction in California to a 23% reduction in Missouri, however, a continued reduction in carbon intensity and energy efficiency improvements in associated commercial buildings are essential for realizing the potential environmental benefits of drone delivery. Unfortunately, the article is of an older date, received in Nature in October 2015 and published in February 2018, so the results may be different in upcoming years.

4.4 Operation Costs

Although ADRs can reduce the number of trucks and drivers, the difference in the technical specification and operational setting will influence the operational costs in determining if there is a clear advantage of either technology over the other. Referring back to the study by (Clément Lemardel ́ea., 2021) who modelled three delivery scenarios shown in Figure 1, within Barcelonas historical centre and a Paris suburb. Within the Paris suburb scenario, the model showed which used a parcel density between 40 – 200 parcels per km2 bounded to a service area of 9km by 20 km grid. The low end of parcel density showed there was a 15% difference in cost between the worst performing routing, traditional route + storage lockers (2.1 euros), and the best-performing routing truck-launched UAVs. (1.8 euros) Interestingly if compared to a scenario of a higher density of 200 parcels per km2 or higher, the traditional delivery route + storage lockers achieved the lowest operational cost per package. Meanwhile, ADRs perform better than traditional routes but were unable to achieve better operation savings than UAVs or traditional routes and storage lockers in any density. Cost and energy optimal did not align within this scenario as the ADRs were the most optimal in terms of energy usage.

Within the Barcelona city centre scenario which has a high density of parcels (150 – 600 parcels per km2) bounded by a small service region of 2km by 1.5 km grid, different results emerged. All traditional routing methods are not competitive in any density scenario with either ADRs or UAVs at least halving per delivery cost. ADRs are more cost competitive in a higher-density scenario than UAVs with cost curves intersecting around 225 – 250 parcels per km2. Cost and energy optimal results were identical in this scenario.

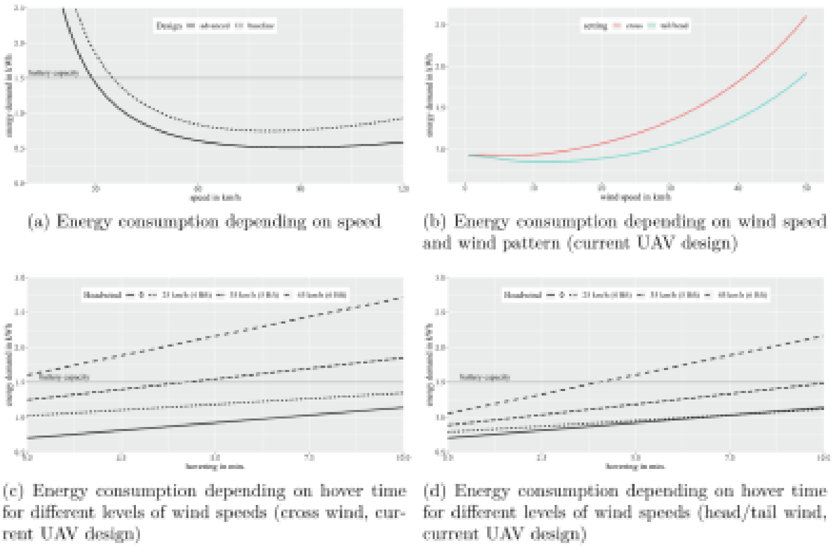
It can be concluded that either autonomous technology can reduce costs but the advantage of either technology over the other is not clear. However, the results show the most optimal technology is dependent on the urban settings in which the technology is operated, and even traditional routing can exceed either technology. The author of the study, however, acknowledges the uncertainty of assumptions used for the inputs within the study and showed many of the inputs, technical or setting related, are sensitive.

5. Technology and Limitations

Drones and ADRs can be negatively affected by difficult weather, such as rain, snow, and high winds, which could impact their reliability and efficiency. While drones and ADRs can potentially reduce energy consumption and emissions, their actual performance depends on factors like traffic conditions, payload, and operational settings. Their deployment may require additional infrastructure, such as warehouses, charging stations, and maintenance facilities, which could increase costs and environmental impacts.

5.1 UAV Sensitivity to Weather Conditions:

Wen-Chyuan Chiang, 2019 considered an emission-lowering Vehicle Routing Problem with Drones (VRPD) and found that using drones offers up to 30% of the total CO2e emissions reduction compared to ICE diesel-powered trucks, as seen in Figure 2. The benefits reported, are based on comparing ICE vehicles against drones, not acknowledging EV trucks can also be considered as environmentally friendly parcel deliveries. Moreover, environmental factors such as wind and transport conditions, nor delivery delays have not been studied much in comparative studies.



(a) Energy consumption depending on speed

(b) Energy consumption depending on wind speed and wind pattern (current UAV design)

(c) Energy consumption depending on hover time for different levels of wind speeds (cross wind, current UAV design)

(d) Energy consumption depending on hover time for different levels of wind speeds (head/tail wind, current UAV design)

Figure 2: Energy usage of UAV at different speeds (Kirschstein, 2020)

A study by Kirschstein, 2020, a detailed energy consumption model for drones, considers weather and hovering patterns, where in crosswind conditions, aerial vehicles need to counterbalance air drag to maintain direction, to stay on course, which in return increases power needed, lowering efficiency. In head/tailwind settings, tailwind reduces energy demand on one leg while headwind increases it on the other. An energy-optimal travelling speed exists and hovering for up to 5 minutes requires significant energy demands. Lithium-ion polymer battery capacity lasts only for 4 minutes of hovering in moderate breeze conditions, resulting in a much lower radius of operation for UAVs (Wen Chyuan Chiang, 2019).

5.2 Future UAVs Developments:

As drones are becoming more prevalent in cities ensuring safety and productivity is essential. The development of low altitude airspace management systems (LAAM) is a key topic, with industry operators looking to create multifaceted management systems tailored to their needs, from both government organisations such as NASA or private entities such as Amazon and Google, potentially be used to regulate drones, facilitate flight planning, and ensure safety (Rico Merkert, 2020). Additional technological factors to consider in logistics-oriented UAV purposes include the take-off and landing concepts, and likewise autonomous control capabilities. Most commercial UAV models offer fully automated stations (Scott et al., 2017). However, for Business-to-Customer (B2C) concepts, the UAV should have the capability to come back and land on uneven surfaces or use detachment technologies like ropes (as seen with Flirty and Google) or parachutes (as used by Zipline in Africa) or the newest Zipline Detachments Unit. A study in Lancet found that delivery of health supplies in remote areas of low and middle-income countries (LMICs) was effective, cut delivery times, and reduced blood wastage. In Rwanda, drone delivery resulted in products arriving 79-98 minutes earlier than by road, with a 67%

decrease in blood termination date. Only a small percentage (<1%) of units were damaged during delivery. This study supports the idea that drones can consolidate and ensure timely deliveries to hospitals, potentially improving patient outcomes (Swaibu et al., 2022). In B2C circumstances, it is logical to expect that drones (or their base) must hover until the cargo is entirely lowered, and conditions for detaching the cargo are met, such as waiting for a clear detachment area or the receiving customer's authorization, either by visual cues or app.

6. Limitations of the Research Reviewed

After reviewing various papers, it is unclear if the adoption of autonomous vehicles will have a positive impact on the typical measurable key measurable indicator like cost and environmental impacts. Most points towards ADRs and drone autonomous technology will bring a positive impact when compared to traditional ICE technologies. But if the trend of electrification in transportation
continues, it becomes less clear if a positive impact will result.

There were some significant limitations and assumptions assumed if either technology is fully adopted. There is an explicit assumption there will be sufficient urban space for drones or ADRs to operate. Existing parking spaces may not provide significant space for loading and unloading for motherships but are assumed to be available. (Figliozzi & Jenningsa, 2020) Public concerns and impacts to other users, sidewalk users for ADRs, and air space users for aerial drones are not considered as well as safety and employment impacts. The increased use of ADRs can negatively impact pedestrians and cyclists on sidewalks, and autonomous navigation, collision avoidance, and communication systems still need improvements to ensure the safe and reliable operation of drones and ADRs in complex urban environments. The interaction of drones with other aircraft and aerial animals is not clear. As mentioned previously, drop-off zones designed for drones in urban areas are unknown.

ADRs also have a problem with the last 50 m problem. ADRs cannot climb stairs, ring doorbells, or physically hand off packages. A person must be present to pick up the package. ADRs also assume the delivery window, the time a delivery can take place, is 24/7. Customers must be home to receive parcels and homes creating restricted delivery windows. Homes are also more likely to be occupied during the evenings creating uneven demand which can affect the total ADRs required.

7. References

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