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Last-mile delivery with electric vehicles, unmanned aerial vehicles, and e-scooters and e-bikes

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ABSTRACT

Intense growth of e-commerce over the last years has been recognized to have a strong impact on logistics and transportation, and particularly on different modes of last-mile deliveries in urban areas. Simultaneously, many European regulations have imposed strict environmental limitations in terms of decreased air and noise pollution in urban areas. In such circumstances, logistics and transportation sector needs to offer more efficient and more environmental ways to deliver goods. In this paper, we consider electric vehicles (EV) and different concepts of EVs, like unmanned aerial vehicles, e-scooters, and e-bikes as appropriate solutions for last-mile deliveries from the environmental perspective and lifecycle costs.

1. Introduction

Business-to-consumers (B2C) e-commerce sector has gained an intense growth in recent years and COVID 2020 only increased that growth even further (Figure 1).

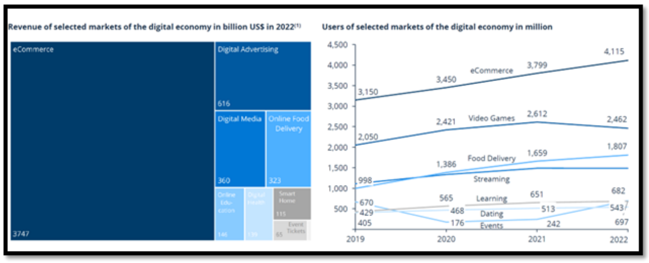

Figure 1. eCommerce sales accounts share - worldwide economy. *Source: https://www.trade.gov/post-pandemic-ecommerce (Accessed 13 November 2023).*

The proliferation of e-commerce over the last years has been recognized to have a string impact on logistics and transportation, owing to the increasing need for last-mile deliveries (i.e., the transportation of goods purchased online to customers' houses) in urban areas (Schöder et al., 2016). Last-mile deliveries take part of 28% in total logistics costs (Ranieri et al., 2018).

At the same time, many European legislations (e.g., Regulation (EC) No 1370/2007) have imposed strict environmental limitations in terms of decreased air and noise pollution. For now, these measures are primarily directed to public transport. However, one can expect that they will gradually be applied in other sectors as well. As an illustration, the Transport White Paper – issued by the Directorate-General for Mobility and Transport, European Commission (28 March 2011) – declared two specific urban goals to be achieved by 2030: (i) halving the use of conventionally fueled cars in cities and (ii) essentially CO_2 free logistics in major urban centers (Siragusa et al., 2020).

In such circumstances, logistics and transportation sector needs to offer more efficient and more environmental ways to move and deliver goods. To overcome upcoming challenges, reshape urban logistics, and transform last-mile delivery the application of innovative solutions becomes imperative. According to statistics, last-mile delivery accounts for 53% of total shipping costs and 41% of total supply chain costs (Moradi at al., 2023).

Among various different solutions, the use of electric vehicles (EV) and different concepts of EVs, like unmanned aerial vehicles, e-scooters, and e-bikes, can be appropriate solutions for last-mile deliveries from the environmental perspective (reduced gas emissions and noise) and lifecycle costs (maintenance and reduced consumption). Therefore, in this paper we consider different concepts of EVs.

The paper is organized in the following way. Section 2, 3, and 4 present last-mile delivery and EV, unmanned aerial vehicles, and e-scooters, respectively. In Section 5 we present industry implications for EVs, and finally, Section 6 provides concluding remarks and future work.

2. Electric vehicles for last-mile delivery

The maximum driving range of EV varies and depends on many factors, but for most EVs it is between 160 and 240 km (Feng & Figliozzi, 2013). The range deteriorates significantly by the impact of weather conditions (e.g., low temperatures) and terrain configuration (e.g., hills). As a direct consequence, the driving range is often not sufficient to complete the imposed logistics tasks and, therefore, charging stations need to deployed on adequate places throughout the transportation network (Figure 2).

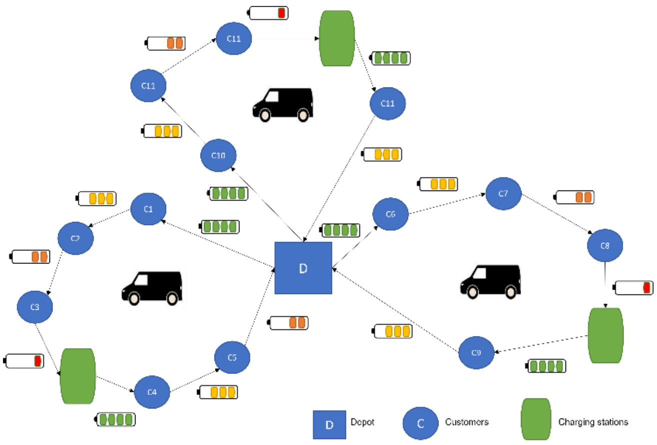

Figure 2. Last-mile delivery with EVs

The main aspects that determine the competitiveness of EVs are the purchase price, battery costs and lifespan, and practical implications of vehicle operations. Between them, battery-related issues, such as specific energy, specific power, and price will have the major role in development of the ecosystem for EV (Ilin et al., 2023). While future lithium-ion cells' specific energy could reach 300 Wh/kg, development of technologies such as lithium-sulfur (Li-S) and lithium-air (Li-air) batteries should allow reaching values above 500 Wh/kg [9]. Zinc-air (Zn-air) batteries are another option in development that could improve specific energy (Yong et al., 2015). Projections for different BEV battery types are provided in Table 1.

Table 1. Projections for promising BEV battery types (Gerssen-Gondelach & Faaij, 2012)

Battery type		Li-S	Zn-air	Li-air
Specific energy (Wh/kg)	< 2025	400	250	500
	> 2025	500	350	1000
Specific power (W/kg)	< 2025	300	Unknown	Unknown
	> 2025	400	Unknown	Unknown
Cost ($/kWh)	< 2025	Uncertain	Uncertain	Uncertain
	> 2025	250-500	100-300	350-700

Recently, specific type of EVs – autonomous delivery vehicles (ADVs), which are self-driving EV, gained increased attention. It is expected that ADV market will grow at a compound annual rate of 11% from 2019. to 200 USD billion by 2029. (AIWS, 2022). As an example, Nuro, Inc., an American robotics company, produces ADV specified for grocery and food delivery (Figure 2). These vehicles are designed to navigate roads safely and deliver items to customers without a driver.

Figure 3. An example of Nuro ADV for last-mile delivery
Source: https://nuro.ai/. (Accessed 22 November 2023).

Although the EV have multiple benefits compared to conventional vehicles with internal combustion, they still have several limitations. EVs are usually middle-size with restricted capacity and they range is limited and depends on battery, chargers, weather conditions etc. In order to handle these challenges, new technologies are developed and new concepts of EVs are constantly introduced. An important parameter during the test process is energy consumption. There are several significant influencing factors (Figure 4).

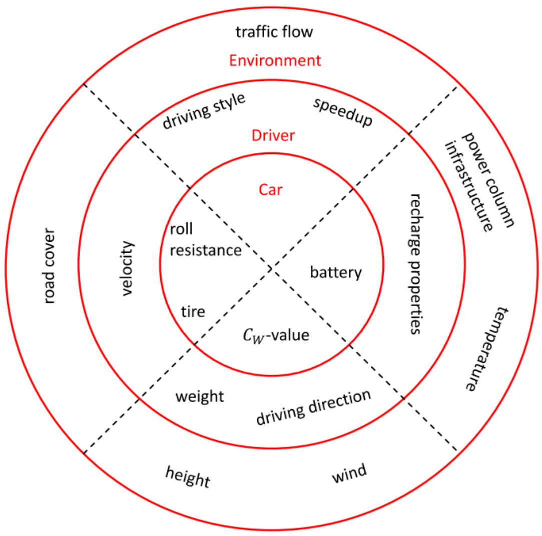

Figure 4. Influence factors on energy consumption by driving an EV (Conradi, 2012)

3. Unmanned aerial vehicles for last-mile delivery

Unmanned aerial vehicles (UAVs) emerged from the online grocery retailing industry. Recently, UAV has attracted much attention and interest from the scientific and industrial communities because they have potential to improve the level of quality of logistics services. Originally, UAVs were restricted to carry only one packet (but not too heavy) at a same time. However, the new generation of UAVs can handle several packets at a time with a maximum load up to 4 kilograms (Banker, 2022). It enabled new last-mile services, such as a two-echelon logistics and distribution network (Figure 5). In the first echelon of the network, the vans transport the grocery packets from depots (i.e., remote warehouses) to the satellites with fixed locations, acting as transshipment sites. In the second echelon, the packets are consolidated and delivered by UAVs from a satellite to the consumers (Li et al., 2024).

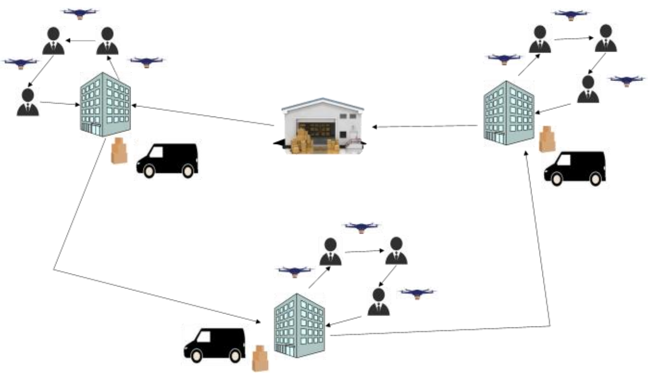

Figure 5. Last-mile delivery with UAVs

In comparison to traditional urban logistics systems, the last-mile delivery by UAVs of online grocery retailing has three distinctive features:

1. The orders randomly sent by customers are usually high frequency and low-volume, and some orders are even made by the same customer in a short time (Zhang et al., 2019).
2. The online platform usually promises a short delivery time for the packets to the customers. Delayed delivery will incur monetary compensation and affect customer satisfaction and experience (Kim & Wang, 2021).
3. The number of UAVs in a satellite is limited due to their high purchase costs and the limited space of the satellite. Therefore, it is usually inefficient to schedule a UAV to deliver a single packet on each trip (Zhang et al., 2019).

Very important aspect of UAVs is policy regulation and restrictions. First, there are restrictions on how close UAVs can fly to people and objects like building. Second, there are limits on the maximum altitude that UAVs can fly and operate. Recommendations from the International Civil Aviation Organization (ICAO) is set to be around 100 meters. Third, some countries define additional no-fly zones or minimum distances from highways, military areas, and congested outdoor venues. Finally, there are minimum distances that UAVs must stay away from airports and airstrips, although exceptions may be granted in special cases (ElSayed, et al. 2024). In Table 2, three categorized degrees of design parameter limitation for distance from property and people and for maximum altitude are shown.

Table 2. Categorized variations in operational policy restriction (Elsayed & Mohamed, 2020)

Category	*Regulatory Limitations*	
	Distance from property and people	**Maximum altitude**
Lean or unrestricted	Restricted over crowds *US, Spain, Malaysia, France, Germany, China, Austria, Italy, Netherlands*	130–155 m *France, Nigeria, Austria, Italy, Colombia, Japan, Chile*
Average	30 m *Canada, Australia, Chile, Japan*	100–122 m *UK, Spain, Australia, Malaysia, US, Canada, Netherlands, China*
Strict	50 m *UK, South Africa, Colombia, Rwanda*	≤100 m *Germany, Rwanda*

An illustrative example of a quadrotor cargo UAV for last-mile delivery is presented in Figure 6.

Figure 6. An example of UAV for last-mile delivery
Source: https://www.ajot.com/news (Accessed 15 November 2023).

Usually, when UAV complete delivery, it returns to the vehicle immediately. However, in some situations the empty UAV can be used to pick up a backhaul packet from a customer (Figure 7). This scenario is described in detail in (Jeon et al., 2021) and interested reader is referred to mentioned paper.

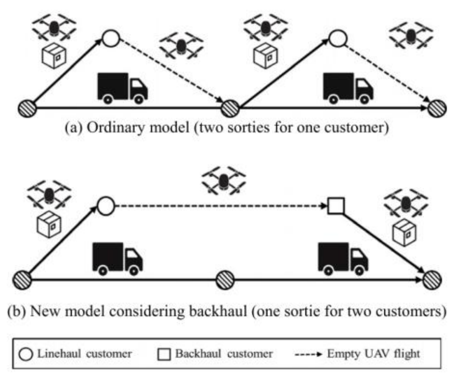

Figure 7. Last-mile delivery with UAVs and backhauls (Jeon et al., 2021)

4. E-scooters and e-bikes for last-mile delivery

Electric scooters (e-scooters) present two-wheeled lightweight electric vehicles. Since they arrive on the market, they managed to transform urban mobility landscape in a manner that they provide alternative for cars, motorcycles, busses, etc. Likewise, e-scooters contribute to variety of solutions when multimodal transport is considered. Their last-mile/first-mile access is considered to be a major advantage compared to some other modes. Existing multimodal behavior (combined e-scooter and transit trips) has been reported to occur for 15% of e-scooter trips in France (https://www.6-t.co/article/trottinettes-freefloating) and 10% of e-scooter trips in Washington, D.C. (Yan et al., 2021). The advantages of e-scooters, such as easy access, no parking, sufficient speed and maneuver operations, small energy consumption, and zero emissions forced logistics companies to include this transportation mode in the last-mile delivery. An illustrative example of e-scooters for last-mile delivery in Figure 8.

Figure 8. An example of e-scooters for last-mile delivery
Source: https://marketplace.eiturbanmobility.eu/products/bruntor-last-mile-delivery-scooter/ (Accessed 19 November 2023).

Electric bikes (e-bikes), similarly to e-scooters, are predominantly used in food delivery due to its flexibility, high speed, ease of travel, and low cost. They move at 15–20 km/h; they are more flexible than other motorized vehicles in urban traffic jams, and their average price, depending on type, is below US $280 (Wang et al., 2021). Besides mentioned benefits of using e-bikes, one should note that e-bikes promote a healthier and more active workforce. However, very important aspect of last-mile delivery with e-bikes is vulnerability of e-bike riders. The crashes often result with human injury (unfortunate often severe). More specifically, 53% of fatal crashes are reportedly due to aggressive driving (AAA Foundation for Traffic Safety, 2016). The most common aggressive driving behaviors are weaving through traffic, hooting to claim the right-of-way, purposefully tailgating another vehicle, and so on (Dong et al., 2021). The typical example is food delivery industry in which drivers need to speed up their delivery in order to reach their next destination as quickly as possible.

An illustrative example of e-bike for last-mile delivery is presented in Figure 9.

Figure 9. An example of e-bike for last-mile delivery
Source: https://gowsalesvs.live/product_details/350145.html (Accessed 17 November 2023).

5. Implications for industry

According to the 2019 report of the world energy outlook series, the future estimation of energy systems indicates that a serious loss will happen by 2040 (World energy outlook, 2019). Tremendous progress and development of information and communication technologies (ICT), particularly in security aspects, offer opportunities for ICT-supported energy transition, including investigation of hydrogen and renewable energy However, there are predictions that the share of electric energy in final consumption will exceed the oil by 2040 (Hook et al., 2012), mainly due to EVs. Having that in mind, EU has targeted a 40% reduction in greenhouse gas (GHG) emissions by 2030 compared to 1990 (European Commission, 2014). This will be a great challenge for the transportation sector and logistics companies.

At the same time, there are many other challenges that need to be overcome in order to enable innovative and sustainable urban logistics concept (Figure 10).

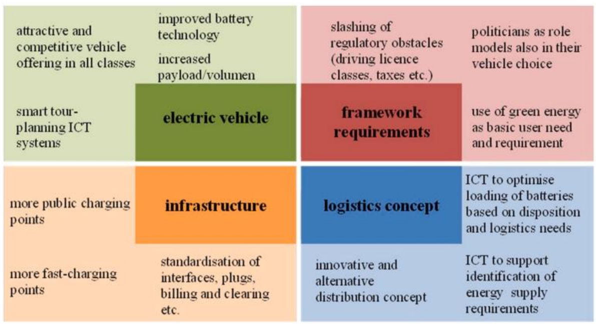

Figure 10. Requirements toward an innovative and sustainable urban logistics concept (Lobig & Ehrler, 2017)

Most importantly, infrastructure needs to be built and managed and for different types of EVs. In particular, parking and charging infrastructure is prioritized. Likewise, adequate regulatory measures are necessary, predominantly for UAVs and e-scooters and e-bikes. Last, but not the least, different planning tools for dynamic routing car reduce traffic jams and sped-up last-mile delivery.

6. Final remarks and future work

Introduction of different types of EVs in distribution and logistics processes transform urban transportation and last-mile delivery. EVs, UAV, and e-scooters and e-bikes reduce transportation costs, pollutions, and noise more efficiently compared to conventional vehicles with internal combustion. However, they all have some disadvantage compared to conventional vehicles. For example, EVs have batteries that need to be charged, which limits their range and sometimes cause long charging periods. UAV are subject to policy regulation and restrictions in terms of weight (number of packets), defined distance from property and people, and defined maximum altitude. Finally, e-scooters and e-bikes are very often involved in crashes due to aggressive driving and other factors as well.

Although EVs and different concepts of EVs can prove beneficial for various delivery businesses, they are especially applicable for last-mile delivery operations due to a fixed and constrained range to travel. Besides e-commerce, there are several different practical examples of last-mile delivery with EVs: milk delivery, grocery delivery, food delivery, home service deliveries, retail delivery, and so on. In order to measure the impact of EVs in all previously mentioned sectors, decision-makers can use key-performance indicators (KPI) for the purpose of monitoring. KPI can include duration of a charging, battery charge level of each EV, network of chargers, and so on.

It is important to note that this research is primarily focused on systematization of various EV concepts in the last-mile delivery. Accordingly, there are several limitation of this study. First, safety aspects of some of EV modes, such as UAVs and e-bikes, are not discussed in detail. Second, disposal of batteries, which can be hazardous to the environment is beyond the scope of this research.

Future research on this topic can explore several directions, according to theoretical and practical perspectives. From theoretical perspectives, one possible extension is to consider a specific class of combinatorial optimization problems: the electric vehicle routing problem, taking battery constraints and charging operations into account. Another possible extension is to consider the location routing problem, where a set of potential stop points for autonomous delivery vehicles are predetermined. From industry perspectives, one possible extension is to consider various battery technologies. For example, besides lithium-ion cells, development of new batteries, such as lithium-sulfur (Li-S), lithium-air (Li-air), and zinc-air (Zn-air) batteries, can be explored. Another possible extension is to consider legislation and regulatory issues. Finally, the research can be focused on accident analysis.

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