Alverhed *et al.*
European Transport Research Review (2024) 16:4
https://doi.org/10.1186/s12544-023-00629-7

European Transport Research Review

REVIEW Open Access

Autonomous last-mile delivery robots: a literature review

Elin Alverhed[1], Simon Hellgren[1], Hanna Isaksson[1], Lisa Olsson[1], Hanna Palmqvist[1] and Jonas Flodén[1*]

Abstract

This literature review investigates how self-driving autonomous delivery robots (ADRs) impact last-mile deliveries, add value to the logistics and transport industry, and contribute to creating competitive business models. Autonomous vehicles are still a developing technology and ADRs could possibly be one of the solutions to the last-mile problem, in particular in cities and for urban freight with an increasing number of parcels to deliver. Last-mile delivery is also changing as e-commerce and more demanding customers emerge. Such development, however, faces challenges regarding infrastructure, externalities such as CO_2 emissions, and shorter delivery-time requirements. This review, focused on ADRs, reveals four major themes (operations, infrastructure, regulations, and acceptance) through which we explain the barriers and benefits of using ADRs for last-mile deliveries. The review shows that the operations of ADRs can impact last-mile deliveries by lowering costs, optimising the use of time, and reducing externalities. The review also shows that the foundation of last-mile infrastructure would have to change if ADRs are to be used to a greater extent. Regulations for ADRs are still not yet in place, which makes the market somewhat confused. The acceptance of ADRs in society is another challenge because the innovation of ADRs is still new and unfamiliar. Altogether, the use of ADRs for last-mile deliveries shows great potential, based on the promising results of the articles reviewed. However, most studies on ADRs have been theoretical in nature, such as models, which highlights the need for real-world case studies and implementations.

Keywords Autonomous, Last-mile, Delivery, Vehicle, Review, Urban freight, Autonomous delivery robots, Freight, E-commerce, City logistics

1 Introduction

The rapid increase in e-commerce and online shopping has sparked a similarly rapid, widespread increase in parcel deliveries. In Sweden, e-commerce increased by 18% per year on average between 2005 and 2019, with a further increase of 40% in 2020 during the COVID-19 pandemic [1]. In turn, its growth has led to increased challenges for last-mile deliveries [2]. According to Bosona [3], last-mile delivery refers to the last transportation part of a supply chain. Changes in shopping behaviour and urban population growth have made last-mile delivery a particular problem in urban settings that causes challenges with congestion, delivery times, and sustainability [2, 4]. This is particularly challenging in areas with a high level of urbanization and a high share of e-commerce, such as Europe and the US. Further, innovative transport modes and systems are rapidly changing the conditions for last-mile deliveries. At the same time, customers demand quicker, more predictable, and more flexible deliveries [1, 5]. This leads to last-mile delivery being an expensive and inefficient part of the supply chain [6].

Simultaneously, technology is making huge leaps in digitalization and autonomous vehicles, with significant research ongoing [7]. Autonomous vehicles are increasingly becoming commercially available and spreading into new areas. Automated guided vehicles (AGVs) have

*Correspondence:
Jonas Flodén
jonas.floden@handels.gu.se
[1] Department of Business Administration, School of Business, Economics and Law, University of Gothenburg, Gothenburg, Sweden

been commonplace in warehouses for decades [8] and, more recently, have found their way onto sidewalks in the form of autonomous delivery robots (ADRs). The externalities, together with the increase in e-commerce and urbanization mentioned above, have put pressure on finding innovative solutions to make last-mile deliveries more efficient. One way of solving this problem could be by using new advanced technologies in order to develop automated delivery systems. This could possibly create a more efficient and more sustainable last-mile delivery system [9].

Hoffmann and Prause [10] argued that autonomous vehicles such as ADRs can be used for the last-mile delivery of products with the purpose of creating value for businesses. For example, one of the leading companies in the industry, Starship Technologies, is already running parcel and grocery services made by ADRs in London and Washington, DC. These autonomous robots currently cost approximately US $5500, weigh 35 kg, can carry up to 20 lb (10 kilos) of goods, travel at a pedestrian speed of 6 km/h, and deliver to customers within a radius of four miles (6.4 km) ([11, 12], Starship [13]). Other examples include Kiwibot, which performs food deliveries at university campuses in California; Amazon Scout, which makes parcel deliveries in a few cities in the United States; and DHL's PostBOT being tested in Germany. However, those and other examples are relatively small-scale, and many resemble pilot projects. Several projects focus on limited areas such university campuses. The ADRs are typically battery-powered, small, box-like structures with four to six wheels and a cargo compartment on the top, although other designs such as walking robots also exist (see Figs. 1, 2).

Fig. 1 A Starship Technologies ADR. Photo: Wikimedia Mbrickn CC-BY-SA-4.0

Fig. 2 A Kiwibot ADR. Photo: Wikimedia Ganbaruby CC-BY-SA-4.0

The aim of this paper is to investigate how ADRs could impact last-mile deliveries and to identify challenges and opportunities for their introduction. It will further identify gaps for future research. To achieve this, a literature review is presented that focuses on ground-based ADR systems, thus not including other types of autonomous vehicles such as drones and larger autonomous trucks and vans. The use of drones for last-mile deliveries is still much in its infancy and faces a significant number of mode-specific challenges relating to the use of air space, landing zones etc. (for a review of challenges, see [14].

The paper is structured as follows. Section 2 discusses the method used, after which Sect. 3 presents the review of the relevant literature, divided into four subsections (operations, infrastructure, regulations, and acceptance). Section 4 discusses the results of the literature review, and Sect. 5 offers our conclusions.

2 Method

This literature review investigates how ADRs impact last-mile deliveries and identifies challenges and opportunities for their introduction. To ensure scientific relevance, we restricted the review to peer-reviewed articles and conference papers written in English. Using the search string "last-mile delivery" OR "last-mile" AND "robots" OR "autonomous vehicles" OR "self-driving" OR "delivery robots" OR "autonomous delivery robots", we performed a search for literature in October 2023 in Scopus and Google Scholar, as well as used both forward and backward snowball selection. The inclusion criteria were that the articles should address the combination of ADRs and last-mile deliveries in freight but not focus on technical aspects of ADRs' design or on the development of mathematical routing algorithms.

A total of 288 articles were identified as potentially interesting. In the first stage of the selection process, the titles of all articles were read, and ones that clearly focused on passenger transport, technical design, or routing algorithms or were otherwise clearly out of scope were excluded. After the titles were reviewed, 113 articles remained. The second stage involved reading the abstracts of the articles. Using the same exclusion criteria mentioned above, we reduced the number of articles to 57. In the third stage, we read those 57 articles in full and ultimately identified 27 articles that met the criteria for inclusion in the review. The results in the articles were subsequently analysed and compared to explore how ADRs impact last-mile deliveries and to identify challenges and opportunities for their introduction.

Before presenting the literature review, we should acknowledge that the results of the review are based on a limited number of articles. For that reason, it is challenging to generalise the results because they may vary depending on what kind of self-driving vehicles are used and in what context, as well as on the environment in which last-mile delivery is executed.

3 Literature review

After analysing the results from the literature reviewed, we identified four themes: operations; infrastructure, regulations, and acceptance. The results of the review are accordingly divided into those four themes in this article (see Table 1 for a summary of the articles). The theme of operations largely refers to potential benefits gained from ADRs, whereas the remaining themes largely address challenges in using them.

As the reviewed articles reveal, the topic of ADRs for last-mile deliveries has gained popularity only recently, for no articles on the topic published before 2018 were found, most likely due to as a consequence of the rapid technological development making these autonomous deliveries possible. This can also be seen by the few real world implementations studied. In fact, only one article examines ADRs on public streets, while another two examine the more limited contexts of campuses and laboratory environments, respectively. By region, most articles cover Europe and the United States. The articles all focus on how ADRs can solve the last-mile delivery problem in urban and suburban areas, thereby indicating that researchers see the greatest potential for autonomous deliveries in urban settings with dense populations and short transport distances. Moreover, even though different terms for ADRs are used in the articles, the general term used in this review is ADR. In the following subsections, the four themes are presented to illustrate the impacts of ADR on last-mile delivery as explained in the examined literature.

3.1 Operations

Operations refers to the physical operations of ADRs, including aspects such as planning, routing and scheduling, costs, and externalities. In this review, the theme of operations is divided into four parts: operating processes, costs, time, and externalities.

3.1.1 Operating processes

Two major types of suggested operating processes can be identified in the literature: truck-based and hub-based ADRs. No other operating procedures were found. Most reviewed articles focus on truck-based operating approaches, four types of which are suggested (see Fig. 3):

1. *Direct truck-based ADRs*, in which trucks carrying several on-board ADRs operate from a main hub. Each truck drives into a neighbourhood and dispatches and retrieves ADRs from the truck, temporarily parked at an appropriate location. After returning to the truck, the ADRs are loaded with new freight, and the truck continues to the next neighbourhood [10, 11, 20, 26]. The three other approaches are different adaptions of using direct truck-based ADRs:
2. *Flexible truck-based ADRs*, in which the ADRs are dropped off and picked up at different locations [9],
3. *Cyclic truck-based ADRs*, in which trucks return to the hub after dropping off ADRs, pick up more ADRs, and later return to simultaneously drop off those ADRs while picking up the other ADRs again [12],and
4. *Depot-assisted truck-based ADRs*, in which ADRs are dispatched from trucks but return to the local ADR depot or hub by themselves so that the trucks do not to have to wait for them. Thereafter, the trucks pick up new, recharged ADRs at the depot during their routes [16, 22, 28].

Direct truck-based ADRs offers the lowest utilisation of the truck because it remains idle while the ADRs perform deliveries. The truck additionally needs to wait for the last ADR to return, even if it has been delayed. It can also be a challenge to find appropriate locations to park in a city. Nevertheless, the approach reduces the need for planning compared with the flexible and cyclic truck-based ADR approaches. In those approaches, the utilisation of the truck is greater, but it also introduces the need to coordinate the truck's arrival with the ADRs. The flexible and depot-assisted approaches also impose greater demands on the routing of ADRs to new depots and on ensuring that there is space available at the depots. In the depot-assisted approach, it may also be challenging, as well as costly, to find appropriate locations in a city

Table 1 Reviewed articles

Article	Themes				Scope	Method	Real-world implementation
	Operations	Infrastructure	Regulations	Acceptance			
Alfandari et al. [15]	X	X			The effect of tardiness on the service quality of ADR deliveries	MILP model	No
Boysen et al. [16]	X	X			Evaluation and scheduling of truck-based ADRs	MIP model	No
Bakach et al. [17]	X				Evaluation of ADRs with truck deliveries to local hubs	MIP model	No
Chen et al. [11]	X	X		X	Evaluation and routing of truck-based ADRs	MILP model	No
Edrisi and Ganjipour [18]				X	Customer acceptance of ADRs	Survey and structural equation modelling (SEM)	No
Ganjipour and Edrisi [19]				X	Customer acceptance of ADRs	Survey and SEM	No
Garus et al. [20]	X	X			Sustainability assessment of ADRs	MCDA	No
Gehrke et al. [21]				X	Pedestrians' and bicyclists' interactions with ADRs	Video-recording	Test on university campus
Heimfarth et al. [22]	X				Evaluation of ADRs with truck deliveries to local hubs	MIP model	No
Hoffmann and Prause [10]	X	X	X	X	Regulatory framework for ADRs in Estonia	Interviews, desktop analysis	No
Jennings and Figliozzi [12]	X	X	X		The impact of regulations and technical capabilities of ADRs by analysing cost, time, and efficiency effects	Desk research, model	No
Kapser and Abdelrahman [23]				X	Customers' acceptance of ADRs	Survey and SEM	No
Koh and Yuen [24]				X	Customers' acceptance of ADRs	Survey and SEM	No
Lemardelé et al. [25]	X				Life-cycle analysis of ADRs with truck deliveries to local hubs	LCA analysis	No
Li et al. [26]	X				Life-cycle analysis of truck-based ADRs	LCA analysis	No
Oulmakki et al. [27]				X	Customers' acceptance of ADRs	Survey and SEM	No
Ostermeier et al. [28]	X	X	X		Evaluation and routing of truck-based ADRs	MIP model	No
Pani et al. [29]				X	Public acceptance of ADRs during the COVID-19 pandemic	Survey	No
Poeting et al. [30]	X	X			Evaluation of ADRs from micro depots	Simulation	No
Puig-Pey et al. [31]				X	Public acceptance of ADRs	Survey and interviews	Lab environment

Table 1 (continued)

Article	Themes				Scope	Method	Real-world implementation
	Operations	Infrastructure	Regulations	Acceptance			
Saravanos et al. [32]				X	Customers' acceptance of ADRs	Survey and SEM	No
Schaudt and Clausen [33]	X	X			Evaluation and scheduling of ADRs from micro depots	MIP model	No
Schnieder et al. [34]				X	Estimations of land-efficient mobility for ADRs	Simulation	No
Simoni et al. [9]	X	X		X	Evaluation and scheduling of truck-based ADRs	IP model	No
Sindi and Woodman [5]		X	X		Evaluation of the impact and barriers of ADRs for last-mile delivery in the UK	Interviews	No
Weinberg et al. [35]				X	Pedestrians' interactions with ADRs in Pittsburgh, PA, USA	Ethnographic observations and interviews	Pilot on public streets
Yuen et al. [36]				X	Customers' acceptance of ADRs	Survey and SEM	No

to establish several hubs. The driving distance of ADRs might also increase if the depots are far apart. Overall, the direct truck-based approach is the easiest to operate at the cost of the low utilisation of the truck. From an operations standpoint, it is also similar to how a human delivery driver would operate by parking the van and delivering parcels on foot. Meanwhile, the depot-assisted and flexible approaches allow the greater utilisation of the truck at the cost of an increased driving distance for ADRs and increased requirements in planning.

The other major suggested operating approach involves establishing a fixed local micro-hub in each neighbourhood and dispatching ADRs from there [15, 17, 25, 30, 33]. Although micro-hubs can vary in size, Poeting et al. [30] have suggested creating very small micro-hubs with only one ADR. Shipments are delivered by truck to the micro-hub, where each shipment is queued until the customer's preferred delivery window arrives.

3.1.2 Costs

The literature also presents different aspects of costs when using ADRs and the impacts on such solutions for last-mile delivery. There appears to be a consensus that ADRs could allow reduced costs, although all estimates are based only on theoretical studies and small-scale tests. A decreased operating cost is the principal factor driving the implementation of ADRs. According to Hoffmann and Prause [10], the cost of delivering one unit is less than 1 euro per delivery, which is 15 times less expensive than other delivery services used for the same purpose. Boysen et al. [16] have estimated that their truck-based system results in lower costs, time savings, and more secure deliveries, despite the investment and operating costs required by depots. Similar results were also found by Garus et al. [20]. Moreover, the same conclusion regarding cost savings has been supported by Chen et al. [11], who highlighted the importance of finding innovative ways of making last-mile deliveries and that using ADRs, in some cases, can result in lower costs. Added to that, Ostermeier et al. [28] have shown that using truck-based ADRs can reduce the last-mile delivery costs by up to 68% compared with regular truck deliveries. Similarly, comparing truck deliveries to a local hub with robots to regular truck deliveries, Bakach et al. [17] calculated saving in operating costs of over 70%, and even greater in instances with customer delivery time windows. Another study by Heimfarth et al. [22] has suggested savings up to 43%.

According to Jennings and Figliozzi [12], autonomous deliveries are time-efficient, which translates into increased cost-efficiency. In their study conducted in the United States, those authors found that, at least in theory, using sidewalk ADRs can save time and therefore money. The same argument has been made by Schaudt and Clausen [33], who concluded that optimised distribution leads both to time and cost savings.

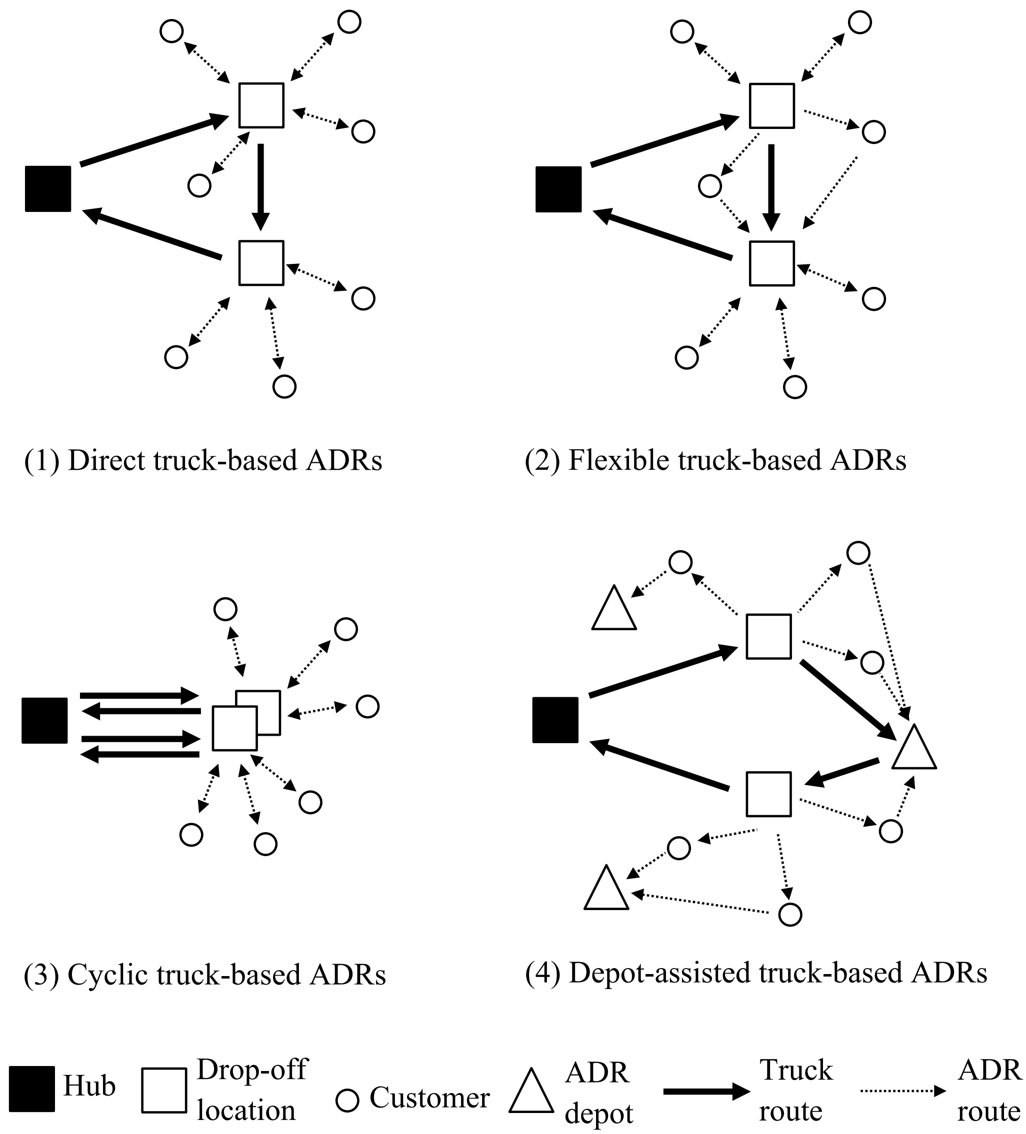

Fig. 3 Suggested truck-based operating processes

The cost savings include savings in personnel costs, since ADRs do not need a salary, unlike in the traditional trucking method, where the trucker must get paid for the work. Furthermore, ADRs would not require any breaks during working hours [33]. According to Simoni et al. [9], using ADR-assisted delivery trucks also generates high-quality outcomes, including time savings for last-mile deliveries.

However, Alfandari et al. [15] have indicated that using ADRs presents a challenge in today's societies due to security risks and the high cost of implementation. They also mentioned that one solution is to hire a third-party logistics service provider using ADRs to avoid investment costs but still gain the advantages. Nonetheless, investments in ADRs and hubs present a significant cost [12]. The investment cost of a denser network of robot depots, however, has to be balanced against delivery performance [16]. Meanwhile, security concerns include the risk of theft from ADRs, such that the goods compartment has to be designed to resist break-ins and can be opened only with a code sent to the customer. ADRs can also be equipped with cameras, GPS, and weight sensors to record whether cargo is removed [12]. Although ADRs are typically quite heavy, it is also not unthinkable that entire ADRs may be stolen if known to carry exceptionally high-value goods.

3.1.3 Time

Improvements in time utilization can be connected to savings in operating costs from a company's perspective and to improved delivery times from the customer's perspective.

Alfandari et al. [15] have analysed the operational challenges of delays in last-mile delivery and how they may be solved by route optimisation for a hub-based ADR system. In such optimisation, the chief goal is to reduce tardiness according to three criteria: total tardiness, maximum tardiness, and the number of late deliveries. The best solution depends on several factors, including the speed of the ADRs, the number of facilities, and the number of customers. Late deliveries decrease as the number of hubs increases [15], as further discussed by Schaudt and Clausen [33], who found that using ADRs for small deliveries over short distances can decrease the number of late deliveries. Jennings and Figliozzi [12] have also demonstrated that sidewalk ADRs can save time and thus increase customers' satisfaction because they can obtain their products even faster.

Chen et al. [11] have suggested that when the time window for delivery is tight, ADRs are effective in making quicker, more efficient deliveries. Similar to Jennings and Figliozzi [12], they have also estimated that, with ADRs, customers could obtain their parcels quicker, there could be fewer vehicles on the roads, and delivery performance could be improved.

Last, in their study on a truck-based ADR system, Simoni et al. [9] found that ADRs should ideally be deployed in a limited area characterised by congestion and many customers, due to the low operating speeds of ADRs. Their results suggest that, despite operating at low speeds, ADRs can potentially provide significant savings in travel time, especially when the same ADR delivers multiple orders.

3.1.4 Externalities

The externalities of ADRs refer to factors that impact actors outside the ADR system. According to the reviewed literature, externalities can affect the use of ADRs, the most commonly mentioned ones being CO_2 emissions and congestion.

Views on whether ADRs contribute to reduced CO_2 emissions differ, however. Poeting et al. [30] developed a simulation model of a hub-based ADR system and showed that using ADRs does not make much difference in total distance travelled or total CO_2 emissions compared with traditional truck deliveries. At the same time, from the customer's perspective, the possibility of choosing specific time windows improves the level of customer service. Li et al. [26] performed a life-cycle assessment (LCA) of a system with delivery trucks and bipedal walking ADRs for the final distance, which they compared with a conventional delivery system. The results showed that the conventional delivery system had lower greenhouse gas (GHG) emissions, while the automated option had up to 10% higher emissions depending on the set-up. More recently, Lemardelé et al. [25] estimated that the LCA-based impact on GHG emissions in a system using local micro-hubs was higher than with traditional truck delivery, which they largely attributed to the need for battery replacement. The impact of GHG emissions during operations was also estimated to be lower than that of truck delivery. By comparison, Ostermeier et al. [28] studied a truck-based ADR system, and their results, supported by the findings of Garus et al.'s [20] similar study, revealed that autonomous delivery systems reduce CO_2 emissions. They additionally showed that the distance travelled by truck can be reduced by using ADRs, which would consequently lower emissions in the local area by up to 60%, according to their calculations. According to the authors, those findings can act as guidance both in the operation and planning of truck-based ADR systems [28]. Added to that, Garus et al. [20] have suggested that using a truck-based ADR system also affords the best impact on social equity, safety, air pollution, and climate stability.

Concerning congestion, ADRs may reduce congestion on roads, although using them risks relocating congestion to the sidewalk instead. Jennings and Figliozzi [12], for instance, have underscored the potential of using sidewalk ADRs to reduce congestion, but that this could also have a negative outcome. Sidewalk ADRs show potential in reducing the number of vehicles on the road, which would have positive effects in urban areas where externalities are becoming increasingly problematic. Even so, a negative effect of using sidewalk ADRs would thus be creating other externalities, including congestion on sidewalks and safety for pedestrians in urban areas. However, Simoni et al. [9], based on the results of their study, have suggested that that type of last-mile delivery could benefit customers located in the city centre given high levels of congestion there. However, in contrast to the majority of articles reviewed, Hoffmann and Prause [10] have suggested using ADRs in areas with less traffic due to the limited delivery zones for ADRs, along with the problem of sharing sidewalks with other traffic and pedestrians.

An aspect that may help reduce congestion and stress on the infrastructure was mentioned by Chen et al. [11]. They found that customers could obtain their parcels more quickly with ADRs, which would result in fewer vehicles on roads. The reduction in vehicles in a truck fleet when using a truck-based ADR system compared with a regular truck-only system has also been highlighted by Ostermeier et al. [28], who have asserted that the reduction may lessen the impact of congestion on infrastructure, thereby making the roads less crowded.

3.2 Infrastructure

Infrastructure refers to the facilities needed to operate an ADR system. A recurring theme in the literature is the question of infrastructure—that is, what will happen, and how, if or when ADRs are implemented on a larger scale in the real world. Although most of the reviewed articles present hypothetical situations and mathematical calculations in answer to that question, their theoretical findings have not been tested in large-scale real-world situations.

In Sindi and Woodman's [5] article on the impacts of and barriers to using ADRs for last-mile delivery, in which they interviewed people in the industry, one of the most prominent questions raised was what kind of infrastructure is needed to implement the use of ADRs. Simoni et al. [9] have also addressed possible problems and challenges in implementing self-driving delivery systems, including about regulations, safety, and operating such a system in crowded areas, which requires pedestrians to share sidewalks with ADRs. Making those deliveries in congested city centres may intensify challenges for security and sidewalk-sharing and consequently put stress on infrastructure. Gehrke et al. [21] recorded the interaction between pedestrians and ADRs on a university campus and observed that ADRs caused pedestrians to change paths to avoid colliding with them. In those cases, conflicts were often initiated by ADRs while overtaking pedestrians due to their higher speed or by crossing in front of pedestrians, and the most severe conflicts occurred at intersections. Nuancing those findings, Jennings and Figliozzi [12] have reported that ADRs are stopped 30% of the time due to waiting for pedestrians, crossings, and congestion.

Another aspect that may impact infrastructure is the speed of ADRs when sharing sidewalks with pedestrians. Poeting et al. [30] have asserted that the primary challenges of using ADRs instead of a truck are the driving range, driving speed, and surrounding infrastructure. Poeting et al. [30] estimated ADRs as moving at a walking speed of around 3–4 km/h, other studies, including Alfandari et al.'s [15], have estimated ADRs to operate at a considerably faster speed of 5–6 km/h, which more closely aligns with the average pedestrian's speed of 5 km/h [9]. Alfandari et al. [15] also concluded that increasing the speeds of ADRs up to 10 km/h would increase effectiveness but that higher speeds would not be beneficial. Even so, in a truck-based system, a higher speed would mean not only more efficient service but also less time waiting for vehicles that are picking up and dropping off ADRs [11]. None of the reviewed studies, however, examined the potential correlation between the speed of ADRs and the risk of accidents or sidewalk-infrastructure utilization. Schnieder et al. [34], however, in estimating the land use efficiency of ADRs, concluded that ADRs require more *time area*, defined as the "ground area consumed for movement and storage of vehicles, as well as the amount of time for which the area is consumed" than other delivery options, because usually only one parcel can be delivered at a time. ADRs would thus use more urban space than traditional delivery options.

Another examined aspect that can relate to infrastructure is ADRs' need for city depots when using a hub- or truck-based system with ADR depots, as suggested by Boysen et al. [16], Garus et al. [20], Ostermeier et al. [28], and Schaudt and Clausen [33]. Using those kinds of systems requires depots for ADRs that are in proximity to where their deliveries are made, which can be challenging in urban settings given the rather high competition for space.

3.3 Regulations

As presented in this section, various barriers to and challenges exist for regulations and policies regarding ADRs and last-mile deliveries, as mentioned in a few of the reviewed articles. Many such regulations already actually in place seem to be meant mostly for urban areas, because those areas are where most ADRs operate.

According to Hoffmann and Prause [10], attempts have been made to create regulatory frameworks regarding ADRs analysing political, social, and sustainable perspectives. Although only some countries have such regulations in place while others remain sceptical about adopting new traffic laws, countries such as Estonia have enacted laws to regulate how ADRs share sidewalks with pedestrians. Of course, conflicts could arise when different regulations are implemented in different countries and regions. In the United States, for example, where both Idaho and Virginia allow ADRs, Idaho enforces a legal maximum weight of 80 pounds (36 kg), whereas Virginia allows no more than 50 pounds (23 kg) [10]. The implementation of ADRs could thus face divergent laws and regulations even within the same country. Such different regulations can complicate how land-robot delivery companies define their develop their business models to generate a competitive advantage from using ADRs for deliveries to customers [10].

Jennings and Figliozzi [12] have also described problems with regulations regarding ADRs in the United States. There, seven states and three cities have implemented such regulations. San Francisco, CA, for example, has restrictions concerning speed and insurance, as well as requires permits for all ADRs, which are valid for

180 days. The city also requires ADRs to give a warning sound but does not impose a weight limit. According to Jennings and Figliozzi [12], San Francisco's legislation is the most restrictive in the United States, whereas Arizona's is the least restrictive. There, the state enforces restrictions concerning speed limits but not concerning insurance, braking systems, or serial number plates, among other things. Otherwise, ADRs merely have to follow the same laws as pedestrians [12].

Another challenge concerning legislation, one presented by Hoffmann and Prause [10], is the protection of personal data that is not only stored and transferred online but also locally stored in ADRs themselves. In such cases, ADRs risk violating the European General Data Protection Regulation (GDPR) because they indeed collect personal information.

Sindi and Woodman [5] showed that another barrier to implementing ADRs could be government policies and their lack of standardisation, which requires ADR manufacturers to customise the robots that they produce. In their article, Sindi and Woodman [5] offer recommendations for policymakers about establishing regulations for ADRs, including by standardising them. Since ADRs, is a new and rapidly developing technology, policies and regulations are naturally not yet in place. On that count, Ostermeier et al. [28] have suggested that additional research on the use of ADRs can help with evaluating different potential regulations and implementing appropriate ones—for example, about the urban planning that ADRs will require in the future, including zones where they are prohibited or allowed to travel at higher speeds.

3.4 Acceptance

A recurring theme in the reviewed articles is society's acceptance of implementing delivery systems using ADRs. That topic can be viewed both from the customer's perspective and from the perspective of society as a whole.

According to Simoni et al. [9], there might be an issue with operating ADR systems in crowded areas as pedestrians need to share sidewalks. Although the authors did not specifically study that potential conflict, they have argued that it will play a major role in the future implementation of ADR-assisted delivery trucks in last-mile delivery systems and should be considered in future research. On the same topic, Hoffmann and Prause [10] have shown that having to share sidewalks with ADRs have already created conflicts in some places. In the United States, Weinberg et al. [35] conducted ethnographic observations of a test of ADRs in Pittsburgh, PA, and found that the ADRs attracted attention but that pedestrians were largely curious about the ADRs and even helpful—for example, by assisting ADRs that had gotten stuck.

Hoffmann and Prause [10] further argued that significant technological innovations usually initially face huge protests before society accepts them, and such may well be the case with land-based ADRs. The differences in laws between countries might also hinder the use of ADRs instead of making the new technology easier to use. Therefore, the authors have urged patience in the near future in order for society to accept ADRs. Along those lines, Puig-Pey et al. [31] found that users more than 60 years old would not accept ADRs, although younger users had relatively positive attitudes towards the technology.

Chen et al. [11] stated that a crucial aspect of deliveries is that not all customers can accept deliveries made by ADRs—for example, due to access restrictions or the inaccessibility of delivery locations. For that reason, some customers will inevitably need to be served by a standard truck. Even so, ADRs could complement such standard ways of making last-mile deliveries. Since this is a new and innovative way of making deliveries, this could possibly change in the future when once customers have had the opportunity to get used to the technology [11]. Further, Pani et al. [29] found that 61% of customers were willing to pay extra for delivery via ADRs, especially ones classified as "e-shopping lovers" or "omnichannel consumers" (i.e. urban customers who shop both online and in physical stores). Meanwhile, the predominant reason for not being willing to pay extra was satisfaction with current delivery options.

Studies have indicated that the performance of ADRs and attitudes towards them are the most influential factors in gaining customers' acceptance of the technology. A survey conducted by Oulmakki et al. [27] suggests that price does not influence the acceptance of ADRs but rather utilitarian factors, such as expected performance. By some contrast, a survey by Kapser and Abdelrahman [23] revealed price to be the most important factor, followed by expected performance. By even further contrast, a survey by Saravanos et al. [32] identified perceived usefulness as the most important factor, followed by social influence from the opinion held by others. Men were more likely than women to accept ADRs. In other surveys by Edrisi and Ganjipour [18] and Ganjipour and Edrisi [19], acceptance has been shown to be influenced by customers' attitudes towards ADRs. In particular, customers with positive attitudes towards ADRs were relatively likely to use them, whereas customers who perceived ADRs as being complicated were not. The results of yet another survey by Yuen et al. [36] suggest that attitudes towards ADRs is the most influential factor of their acceptance, followed by their perceived usefulness. Last, Koh and Yuen [24], on the topic of home deliveries during the COVID-19 pandemic, have suggested that the most influential factor for using ADRs is whether the service fulfils customers' expectations that the technology does not intrude upon their daily lives and that it practises social distancing.

4 Discussion

As the literature describes, using ADRs in last-mile delivery is a complex challenge. Numerous parameters should be considered, and various problems need to be resolved to enable their effective implementation and use. Many of the challenges are also interlinked, whereby for example both successful real-world implementations and appropriate regulations are needed to gain public acceptance. As Schaudt and Clausen [33] discussed, it is important to find a solution both for increasing goods volumes and rising customer expectations. The literature suggests that an effective usage of ADRs performing on-time deliveries would be better able to meet customers' expectations and contribute to customer satisfaction. This would also result in a greater acceptance in society of this method of delivery. Potentially, dynamic dispatching where the ADR adapts to late orders and changed customer preferences during the day could provide further benefits, although this was not discussed in the reviewed papers. A well-functioning system could also result in decreasing delivery costs for customers, which would also contribute to better customer satisfaction and hence improve acceptance by society.

Notably, there is a lack of academic literature studying real-world implementations. Although some real-world tests have been conducted (e.g. for Starship, Kiwibot, Scout, and PostBOT), they have yet to be thoroughly evaluated in the academic literature. Instead, the literature relies largely on modelling approaches containing various simplifications. For example, several articles that we reviewed describe different types of models to calculate optimal routes and compare ADR-based delivery with traditional delivery via truck. However, because models are always a simplification of reality, various parameters were excluded. Boysen et al. [16], for instance, concluded that ADRs would result in lower costs, greater time-efficiency, and more secure deliveries. Nevertheless, their results are based on an algorithm that assumes that ADRs would not be a bottleneck in operations, which could have contributed to positive results. Similarly, the results of an interview study by Sindi and Woodman [5] also highlight several parameters that have been excluded in the models in other articles as problem areas. Further studies of the real-world implementation of ADRs in last-mile delivery are therefore needed.

A topic not covered in the modelling approaches is the acceptance of ADRs by customers and society. Hoffmann and Prause [10] have argued that new technology typically faces resistance before society accepts and adapts to it, an argument supported by the general theory of cultural lag introduced by Ogburn [37] more than a century ago. As noted earlier, this might be the case with ADRs, which, together with the lack of existing standardised regulations, could result in a further decrease in acceptance. Acceptance is related not only to consumers getting used to a particular type of solution, but also to accessibility and the fact that some people cannot accept deliveries by ADRs for various reasons, such as disabilities or technical constraints. The acceptance of ADRs is also linked to their efficient regulation. A comparison can be made with electric scooters that, in 2018, began flooding the world's major cities. Those shared, dockless e-scooters were available for rent and could be left anywhere when users were finished riding them. The lack of regulations and clashes with pedestrians on congested sidewalks caused urgent calls for bans and regulations as the general acceptance of the scooters plummeted [38]. The unregulated, large-scale introduction of ADRs would likely elicit a similar response. It is therefore important that the future development of ADRs focuses not only on their technical development but also on how they can be better accepted by society. After all, the successful implementation of ADRs is not only a technical matter but also relates to urban development at large and what societies want their cities to look like in the future.

ADRs are currently subject to different regulations in different countries and even in different cities in the same country. However, clear, uniform regulations at the national and international levels would be a significant advantage for ADR manufacturers and logistics operators. Other types of road vehicles, such as trucks, face similar regulations in most regions and countries, which has allowed those vehicles to move across borders and be developed for a broad base of customers. On top of that, standards concerning the design of ADRs are also lacking, which limits interoperability between different systems and manufacturers. In the wide-scale adoption of ADRs in cities, it is likely that different ADR systems will meet and interact, which would benefit from shared standards.

Congestion was also brought up in the reviewed articles. This is something that could be either a solution or a problem regarding the implementation of ADRs. However, studies have yet to take a holistic view on the impact of ADRs from the perspectives of urban planning and traffic engineering. As a consequence, questions such as whether ADRs will operate on roads or on sidewalks and, in the latter case, whether they will have ADR-only lanes or share lanes with bicycles and/or pedestrians have yet to be answered. In the literature that we reviewed, ADRs are imagined as operating on sidewalks, which would thus be shared with pedestrians [15, 30] and have lower land use efficiency than trucks [34]. ADR speeds suggested in the reviewed articles vary from about half the speed [30] of an average pedestrian [39] to twice as fast [15], but the implications for the risk of accidents and pedestrian interaction remain unclear, even when research has shown that conflicts will occur [21]. A lot of traffic in the form of traditional deliveries with trucks could be removed from streets, or at least reduced, if ADRs were implemented. Even so, the congestion would move from the streets to the sidewalks, where ADRs would operate, which could result in restrictions that ban or limit ADRs' operation on sidewalks and even require building a new type of sidewalk for ADRs. Because space in cities is limited, such infrastructure would have to be built by reducing existing road or pedestrian space. The limited range of ADRs would also require more hubs and depots, which, though smaller in size, would present problems both with finding space and obtaining the necessary building permits in already stressed urban areas. The use of truck-based ADR systems, as suggested by, among others, Boysen et al. [16], Hoffmann and Prause [10], and Alfandari et al. [15], could be one option to reduce stress on local infrastructure.

Not only will ADRs affect their surroundings, but the robots themselves could be affected by their surroundings as well. The technology is often presented quite positively in media, and the reviewed articles highlight the technology's possibilities and potential. However, many practical issues have yet to be addressed. For example, what happens if a construction site suddenly pops up in the middle of an ADR's operating path? Are they smart enough to go around, and are they smart enough to go around in a safe way without compromising their own safety and the safety of pedestrians, cyclists, and motorists? Moreover, if an ADR gets stuck for whatever reason, who will travel to it and help it, and how long will it take? How will ADRs handle difficult weather conditions, including heavy snow and ice? Regardless of the solutions, new problems with congestion are likely. Those and other questions stress the need for real-world case studies on using ADRs in last-mile deliveries.

Another aspect of using ADRs to consider is whether doing so will increase or decrease CO_2 emissions. The reviewed articles show different results. Poeting et al. [30] have stated that even if ADRs replace many of the trucks used, CO_2 emissions will not be greatly affected. However, Lemardelé et al. [25], based on their LCA analysis, have suggested that emissions will increase, whereas Ostermeier et al. [28] have argued that the distance travelled by truck is reduced when robots are used, which will indeed reduce emissions in the local area. According to their calculations, emissions could be reduced by up to 60%. Nevertheless, as mentioned—we cannot stress it enough—there is a lack of real-world case studies not based on modelling. A lot of the literature only presents data from models, simulations, or limited tests. However, because potential solutions are only in development, it is difficult to predict how well they will work in practice. The reviewed articles also do not discuss the impact of the type of goods. Most studies (e.g. [12]) have examined general parcel deliveries, but other challenges arise with other types of goods. For example, refrigerated goods require an unbroken cold chain, pharmaceuticals often have added requirements for safety and transport security, and high-value goods face a greater risk of theft. Initially, ADRs will likely be used for conventional parcels in anticipation of further technological development and improved systems. Similarly, the reviewed studies also do not go into depth about how the actual handover of deliveries to customers will take place, including how customers' identity can be verified and how obstacles such as stairs might be managed.

5 Conclusion

Based on the results presented, the following conclusions can be made. Using ADRs potentially impacts last-mile deliveries positively in terms of more secure deliveries and reduced delivery times. It might also have a positive effect on cost reduction and emissions generated from last-mile transportation. Adapting to this new technology potentially provides companies with the possibility to reduce costs and improve customer satisfaction, thereby becoming more competitive. Although ADRs do require implementation costs, they ultimately contribute lower costs in the long term because they reduce the need for trucks. Despite that potential, the system faces a lack of acceptance due to uncertainty, a lack of regulations, advanced technology, and operational challenges. Even though all of those factors present obstacles for ADRs in the near future, our literature review has shown that using ADR systems does increase efficiency, which can shorten total delivery times, increase the security of deliveries, and consequently boost customer satisfaction, which can ultimately nurture the acceptance of the technology in society. However, it should also be highlighted that the results thus far are largely based on theoretical studies, not real-world implementations.

In summary, there are both opportunities and challenges to consider when implementing ADRs in last-mile deliveries. However, because the research previously undertaken in the field has focused on theoretical aspects, further studies and physical tests on how ADRs work in the real world are needed. Managerial implications include the need to work on ADRs' acceptance in society and the need for harmonized regulations to be developed and enacted across different countries. Above all, more real-world case studies are needed to cover all aspects of the complex situation facing the real-world implementation of ADRs. Further studies are also needed into developing harmonized regulations across countries.

Acknowledgements
Not applicable.

Author contributions
EA: Conceptualization, investigation, writing—original draft, SH: conceptualization, investigation, writing—original draft, HI: conceptualization, investigation, writing—original draft, LO: conceptualization, investigation, writing—original draft, HP: conceptualization, investigation, writing—original draft, JF: supervision, investigation, writing—original draft, writing—review and editing.

Funding
Not applicable.

Availability of data and materials
Not applicable.

Declarations

Competing interests
The authors declare no competing interests.

Received: 29 March 2022 Accepted: 21 December 2023
Published online: 08 January 2024

References

1. Trafikanalys. (2022). E-handels effekter på transportsystemet (The effects of e-commerce on the transport system). Transport Analysis Agency, Report 2022:4, Stockholm, Sweden. https://www.trafa.se/globalassets/rapporter/2022/rapport-2022_4-e-handelns-effekter-pa-transportsystemet.pdf
2. Allen, J., Piecyk, M., Piotrowska, M., McLeod, F., Cherrett, T., Ghali, K., Nguyen, T., Bektas, T., Bates, O., Friday, A., et al. (2018). Understanding the impact of e-commerce on last-mile light goods vehicle activity in urban areas: The case of London. *Transportation Research Part D, 61*, 325–338. https://doi.org/10.1016/j.trd.2017.07.020
3. Bosona, T. (2020). Urban freight last mile logistics—Challenges and opportunities to improve sustainability: A literature review. *Sustainability, 12*(21), 8769. https://doi.org/10.3390/su12218769
4. Kiba-Janiak, M., Marcinkowski, J., Jagoda, A., & Skowrońska, A. (2021). Sustainable last mile delivery on e-commerce market in cities from the perspective of various stakeholders. Literature review. *Sustainable Cities and Society, 71*, 102984. https://doi.org/10.1016/j.scs.2021.102984
5. Sindi, S., & Woodman, R. (2020). Autonomous goods vehicles for last-mile delivery: Evaluation of impact and Barriers. In *2020 IEEE 23rd international conference on intelligent transportation systems (ITSC)*. https://doi.org/10.1109/itsc45102.2020.9294558
6. Ranieri, L., Digiesi, S., Silvestri, B., & Roccotelli, M. (2018). A review of last mile logistics innovations in an externalities cost reduction vision. *Sustainability, 10*(3), 782. https://doi.org/10.3390/su10030782
7. Gandia, R. M., Antonialli, F., Cavazza, B. H., Neto, A. M., Lima, D. A. D., Sugano, J. Y., Nicolai, I., & Zambalde, A. L. (2019). Autonomous vehicles: scientometric and bibliometric review. *Transport Reviews, 39*(1), 9–28. https://doi.org/10.1080/01441647.2018.1518
8. Ullrich, G. (2015). The history of automated guided vehicle systems. In: Automated guided vehicle systems. Springer. https://doi.org/10.1007/978-3-662-44814-4_1
9. Simoni, M. D., Kutanoglu, E., & Claudel, C. G. (2020). Optimization and analysis of a robot-assisted last mile delivery system. *Transportation Research Part E: Logistics and Transportation Review, 142*, 102049. https://doi.org/10.1016/j.tre.2020.102049
10. Hoffmann, T., & Prause, G. (2018). On the regulatory framework for last-mile delivery robots. *Machines, 6*(3), 33. https://doi.org/10.3390/machines6030033
11. Chen, C., Demir, E., Huang, Y., & Qiu, R. (2021). The adoption of self-driving delivery robots in last mile logistics. *Transportation Research Part E: Logistics and Transportation Review*. https://doi.org/10.1016/j.tre.2020.102214
12. Jennings, D., & Figliozzi, M. (2019). Study of sidewalk autonomous delivery robots and their potential impacts on freight efficiency and travel. *Transportation Research Record: Journal of the Transportation Research Board, 2673*(6), 317–326. https://doi.org/10.1177/0361198119849398
13. Starship Technologies. (2022). Starship technologies FAQ. Retrieved 20 February, from https://www.starship.xyz/contact/faq/
14. Kellermann, R., Biehle, T., & Fischer, L. (2020). Drones for parcel and passenger transportation: A literature review. *Transportation Research Interdisciplinary Perspectives*. https://doi.org/10.1016/j.trip.2019.100088
15. Alfandari, L., Ljubić, I., Melo, De., & De Melo da Silva, M. (2022). A tailored Benders decomposition approach for last-mile delivery with autonomous robots. *European Journal of Operational Research*. https://doi.org/10.1016/j.ejor.2021.06.048
16. Boysen, N., Schwerdfeger, S., & Weidinger, F. (2018). Scheduling last-mile deliveries with truck-based autonomous robots. *European Journal of Operational Research, 271*(3), 1085–1099. https://doi.org/10.1016/j.ejor.2018.05.058
17. Bakach, I., Campbell, A. M., & Ehmke, J. F. (2021). A two-tier urban delivery network with robot-based deliveries. *Networks, 78*(4), 461–483. https://doi.org/10.1002/net.22024
18. Edrisi, A., & Ganjipour, H. (2022). Factors affecting intention and attitude toward sidewalk autonomous delivery robots among online shoppers. *Transportation Planning and Technology, 45*, 588–609. https://doi.org/10.1080/03081060.2022.2134127
19. Ganjipour, H., & Edrisi, A. (2023). Consumers' intention to use delivery robots in Iran: An integration of NAM, DOI, and TAM. *Case Studies on Transport Policy, 13*, 101024. https://doi.org/10.1016/j.cstp.2023.101024
20. Garus, A., Alonso, B., Raposo, M. A., Grosso, M., Krause, J., Mourtzouchou, A., & Ciuffo, B. (2022). Last-mile delivery by automated droids. Sustainability assessment on a real-world case study. *Sustainable Cities and Society, 79*, 103728. https://doi.org/10.1016/j.scs.2022.103728
21. Gehrke, S. R., Phair, C. D., Russo, B. J., & Smaglik, E. J. (2023). Observed sidewalk autonomous delivery robot interactions with pedestrians and bicyclists. *Transportation Research Interdisciplinary Perspectives, 18*, 100789. https://doi.org/10.1016/j.trip.2023.100789
22. Heimfarth, A., Ostermeier, M., & Hübner, A. (2022). A mixed truck and robot delivery approach for the daily supply of customers. *European Journal of Operational Research, 303*, 401–421. https://doi.org/10.1016/j.ejor.2022.02.028
23. Kapser, S., & Abdelrahman, M. (2020). Acceptance of autonomous delivery vehicles for last-mile delivery in Germany—Extending UTAUT2 with risk perceptions. *Transportation Research Part C: Emerging Technologies, 111*, 210–225. https://doi.org/10.1016/j.trc.2019.12.016
24. Koh, L. Y., & Yuen, K. F. (2023). Consumer adoption of autonomous delivery robots in cities: Implications on urban planning and design policies. *Cities, 133*, 104125. https://doi.org/10.1016/j.cities.2022.104125
25. Lemardelé, C., Pinheiro Melo, S., Cerdas, F., Herrmann, C., & Estrada, M. (2023). Life-cycle analysis of last-mile parcel delivery using autonomous delivery robots. *Transportation Research Part D: Transport and Environment, 121*, 103842. https://doi.org/10.1016/j.trd.2023.103842
26. Li, L., He, X., Keoleian, G. A., Kim, H. C., De Kleine, R., Wallington, T. J., & Kemp, N. J. (2021). Life cycle greenhouse gas emissions for last-mile parcel delivery by automated vehicles and robots. *Environmental Science & Technology, 55*(16), 11360–11367. https://doi.org/10.1021/acs.est.0c08213
27. Oulmakki, O., Verny, J., Janjevic, M., & Khalfalli, M. (2023). Empirical study on consumer's acceptance of delivery robots in France. *International*

Journal of Logistics Research and Applications. https://doi.org/10.1080/13675567.2023.2235290
28. Ostermeier, M., Heimfarth, A., & Hübner, A. (2021). Cost-optimal truck-and-robot routing for last-mile delivery. *Networks*. https://doi.org/10.1002/net.22030
29. Pani, A., Mishra, S., Golias, M., & Figliozzi, M. (2020). Evaluating public acceptance of autonomous delivery robots during COVID-19 pandemic. *Transportation Research Part D: Transport and Environment, 89*, 102600. https://doi.org/10.1016/j.trd.2020.102600
30. Poeting, M., Schaudt, S., & Clausen, U. (2019). Simulation of an optimized last-mile parcel delivery network involving delivery robots. *Advances in Production, Logistics and Traffic*. https://doi.org/10.1007/978-3-030-13535-5_1
31. Puig-Pey, A., Zamora, J. L., Amante, B., Moreno, J., Garrell, A., Grau, A., Bolea, Y., Santamaria, A., & Sanfeliu, A. (2023). Human acceptance in the Human-Robot Interaction scenario for last-mile goods delivery. In *2023 IEEE international conference on advanced robotics and its social impacts (ARSO)*. IEEE.
32. Saravanos, A., et al. (2022). Investigating end-user acceptance of last-mile delivery by autonomous vehicles in the United States. Lecture notes in computer scienceIn M. Rauterberg, F. Fui-HoonNah, K. Siau, H. Krömker, J. Wei, & G. Salvendy (Eds.), *HCI international 2022.* (Vol. 13520). Springer. https://doi.org/10.1007/978-3-031-18158-0_37
33. Schaudt, S., & Clausen, U. (2020). Exact approach for last mile delivery with autonomous robots. *Operations Research Proceedings*. https://doi.org/10.1007/978-3-030-48439-2_49
34. Schnieder, M., Hinde, C., & West, A. (2022). Land efficient mobility: Evaluation of autonomous last mile delivery concepts in London. *International Journal of Environmental Research and Public Health, 19*, 10290.
35. Weinberg, D., Dwyer, H., Fox, S. E., & Martelaro, N. (2023). Sharing the sidewalk: Observing delivery robot interactions with pedestrians during a pilot in Pittsburgh, PA. *Multimodal Technologies and Interaction, 7*, 53. https://doi.org/10.3390/mti7050053
36. Yuen, K. F., Koh, L. Y., Anwar, M. H. D. B., & Wang, X. (2022). Acceptance of autonomous delivery robots in urban cities. *Cities*. https://doi.org/10.1016/j.cities.2022.104056
37. Ogburn, W. F. (1922). *Social change with respect to culture and original nature*. Huebsch Inc.
38. Leefeldt, E. (2019). Electric scooters are igniting new laws, liability concerns and even "scooter rage". CBS News, July 2.
39. Knoblauch, R. L., Pietrucha, M. T., & Nitzburg, M. (1996). Field studies of pedestrian walking speed and start-up time. *Transportation Research Record., 1538*(1), 27–38. https://doi.org/10.1177/0361198196153800104

Publisher's Note

Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.