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SIDEWALK AUTONOMOUS DELIVERY ROBOTS FOR LAST-MILE PARCEL DELIVERY

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Abstract: *The dynamics of e-commerce, combined with the growing number of users and the increasing volume of last-mile consignments, are driving current developments in logistics. As online commerce continues to grow, so does the need for active service providers to deliver courier, express, and parcel (CEP) shipments on time. Autonomous last-mile delivery is said to have the potential to transform the way we receive goods. As these autonomous delivery technologies continue to develop and become more widespread, it is possible to foresee a future where autonomous delivery vehicles seamlessly navigate our roads and sidewalks, bringing our online orders to our doorsteps faster and more efficiently than ever. After a general classification of sidewalk autonomous delivery robots (SADRs), this paper examines how far the development and implementation of these vehicles have progressed and which developments offer the greatest opportunities for ecological and economic use in the future.*

Keywords: *Sidewalk Autonomous Delivery Robots, Last-Mile Delivery, Automated Micro-Vehicles, Sidewalk Delivery*

1. CHALLENGES OF LAST-MILE DELIVERY

The “last-mile” in delivery logistics is the final leg of the delivery process, which is often the most expensive and complex due to the need for individual deliveries to various destinations. It is defined as a one-to-many distribution process. Several shipments are bundled into a tour from a common spatial and institutional point, the so-called break-bulk point, and then delivered individually one after the other. Up to the break-bulk point, large production or transport bundles (shipments) are forwarded in their general direction, this is called the few-to-few section. After this point, these bundles are broken down and re-sorted for the last time. Specific distribution routes are now planned with a specific stop for each shipment, the one-to-many section, or the distribution process [1]. These specific stops are the delivery points, which in turn can be generally divided into the classic home delivery and delivery to pick-up locations.

Three main cost drivers can be identified in the CEP industry. The stop factor, the drop factor, and failed or repeated deliveries. The stop factor describes the average number of stops required per delivery tour to deliver all consignments and, therefore, also indicates the average order density of a delivery area. With higher stop factors, logistics costs can only be reduced through economies of scale or volume effects [2]. The number of consignments per delivery stop describes the so-called drop factor. This indicates how many consignments a delivery driver has to distribute per stop. The number of consignments delivered is significantly higher for tours with a large number of business customers than for tours mainly serving private customers. For the latter, the drop factor is nearly one, while a tour with a drop factor of three or higher indicates a business-to-business (B2B) tour [3]. Failed or repeated deliveries are the third relevant cost driver. If a customer is not present at the first delivery attempt, CEP service providers undertake a second and, later,

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possibly even a third delivery attempt, thus directly increasing the handling costs. Alternative forwarding to a collection point also incurs additional costs [2]. While the parcel delivery rate, i.e., the rate of successful deliveries, is high in the B2B sector, parcel delivery rates to private customers are relatively low. The changed order structure, which is largely due to the success of e-commerce, means that shipment sizes are becoming significantly smaller. The ability of consumers to order products shortly before they are needed and have them delivered as quickly as possible leads to an atomization of shipments, where the transported value is often disproportionate to the transport effort and the associated costs [2].

In recent years, the urban population has become increasingly sensitive to air pollution and traffic congestion. Both problems arise especially in city centres. With its increased volume of shipments and omnipresent delivery vehicles, pointing the finger at the CEP sector is often the simple solution. City politicians then quickly come up with ideas such as introducing a congestion charge, reducing entry times, restricting traffic routes to certain city zones, or tightening emissions standards. However, the exact influence of CEP operations on traffic congestion and pollution is still not proven. Only a handful of studies examine the distribution of traffic volumes within cities. Kummer et al. [4] determine a share of 13.5 percent for vans and other transport vehicles over 3.5 tons for the city of Vienna, while the Department of Transport [5] arrives at a share of 15 percent for light commercial vans in the UK. It needs to be pointed out that these figures include not only CEP-related traffic but also other commercial segments, e.g., deliveries by craftsmen and technicians or food and grocery deliveries, and this reduces the share of CEP services in traffic volume to well below this 13.5 or respectively 15 percent. On the other hand, it is estimated that the contribution of light commercial vehicles and especially last-mile freight transportation to air pollution is comparatively higher, as the vehicles used by logistics companies are often older than those of other road users, drive at slower, more irregular speeds, stop and start more frequently or spend more time idling [6]. Moreover, urban centers, in particular, tend to be congested and do not offer enough space to allow for generous layouts. Short-term traffic disruptions, such as double parking, are particularly problematic in saturated urban road networks, as they reduce capacity and lead to longer travel times and negative externalities. In addition to efficiency losses and increased emissions, frequent stops negatively affect traffic safety [7], and double-parking of delivery trucks in cities severely impacts the already congested traffic flow [8].

To ensure the supply and disposal of goods in cities, municipalities are under increasing pressure to address the problems caused by traffic volumes while at the same time promoting economic growth in the city and ensuring the quality of life of its residents. At present, there is a widespread search for and development of innovative solutions as a way out of the city logistics problem. Current developments focus on reducing emissions and congestion in cities. Innovative approaches to last-mile logistics can help address these issues. The limits of urban capacity, with increasing potential for conflict in the delivery process, and urbanization, i.e., increasing population density in inner cities, should also be considered. As the number of consignments increases, so does the number of delivery vehicles and the risk of congestion in urban areas. By automating the final stage of the delivery process, companies hope to increase efficiency, reduce operating costs, and minimize their environmental footprint. Autonomous delivery robots can reduce the need for human delivery staff and optimize routes. Thus, the operating costs for companies can be significantly reduced, making it an economically attractive logistics option. The environmental impact of delivery is also expected to be reduced through improved route planning and the use of all-electric drives. Another critical factor is the reduction in failed deliveries, as deliveries can be made at times outside regular working hours when recipients are at home.

2. SIDEWALK AUTONOMOUS DELIVERY ROBOTS

Autonomous delivery vehicles can be self-driving cars, delivery robots, drones, or other autonomous platforms. These vehicles are equipped with sensors, cameras, and navigation systems that theoretically allow them to operate without human intervention. In practice, however, they often need to be monitored (remotely) by controllers in order to comply with local and national regulations. Of course, autonomous vehicles must also adhere to laws and standards to ensure they are roadworthy and safe. LiDAR (Light Detection and Ranging), GPS, and advanced camera systems are integral components that facilitate vehicle navigation and object recognition. These sensors provide real-time data to inform decision-making algorithms and route optimization. For transporting and securing parcels or goods, autonomous delivery vehicles can have features such as temperature-controlled compartments for food deliveries or lockable compartments to protect against tampering. The mode of operation is illustrated by the so-called self-driving pick-up, in which the recipient removes their goods from the delivery robot themselves after arriving at the agreed delivery location. This involves a level of customer interaction, such as notifying customers of the delivery’s status, providing delivery window estimates, and offering options for customers to receive their deliveries safely, like using a PIN code to access a delivery compartment on the vehicle. They are equipped with multiple redundant safety systems to prevent accidents and respond to unexpected situations, such as pedestrians crossing their path. Collision-avoidance technology, emergency braking, and obstacle detection ensure they can navigate busy urban environments while prioritizing the well-being of other road users.

The primary motivation for autonomous last-mile delivery is to increase efficiency, reduce delivery costs, and minimize environmental impact. The cost benefits are expected to come from reducing the need for human delivery personnel and optimizing routes. The environmental effects are mainly based on the use of electric drives and optimized routes. Advanced algorithms determine the optimal paths for each delivery, taking into account real-time traffic conditions, road closures, and potential obstacles.

In this paper, we will focus on sidewalk autonomous delivery robots (SADRs) for parcel delivery, thus excluding autonomous (self-driving) cars, drones, automated bicycles, or delivery robots with follow me function. For an impression of a SADR in its operating environment, see Fig. 1.

In the research of Baum et al. [9], autonomous vehicles are first classified as automated micro-vehicles with a maximum tare weight of 400kg and a maximum speed of 45 kph. These vehicles are then further divided into six categories, one of which, “delivery robot without human reference on non-roads”, corresponds to the study area of this paper - SADRs or personal delivery devices (PDDs), as they are sometimes called. The speed for sidewalk operation is limited to a maximum of 6 kph to 16 kph [10; 11], depending on local regulations. The load volume varies between one and four parcels and the corresponding number of compartments. Kovacic et al. describe SADRs as “a fairly small box-like wheeled robot around 70 cm long, 60 cm wide and 60 cm high, with a weight of around 23 kg" and a payload of about 10 kg [12]. Jennings and Figliozzi give an unladen weight of about 18 kg to 36 kg and a payload of about 10 kg to 45 kg [13]. The travel distance is defined as a 6 km operating radius [12] or a range of approximately 6 km to 77 km [13], cf. Table I for an overview of the characteristics.

Figure 1. SADR in its operating environment

Table I.
Characteristics of SADRs

Characteristic	***Value range***
Unladen weight	18 kg to 36 kg
Payload	10 kg to 45 kg
Number of parcels carried	1 to 4 pcs
Maximum travel speed on sidewalks (depending on local regulations)	6 kph to 16 kph
Travel distance	6 km operating radius; approximate range of 6 km to 77 km

2.1. Opportunities

The last-mile is considered one of the most expensive, inefficient, and environmentally damaging parts of the supply chain. It is hoped that automating the last-mile will increase efficiency, positively impacting both operating costs and the environment. The use of SADRs has the potential to reduce the need for human delivery personnel, and the combination of improved computing power, real-time data, and artificial intelligence (AI) makes it possible to plan routes better and faster, react to changes, and optimize routes overall.

One of the main advantages of SADRs is their 24/7 availability. These robots can operate around the clock, providing an "always-on" delivery service not subject to human workforce limitations. Therefore, they can deliver the goods to customers outside the regular operating hours of CEP providers, reaching the customers when they are at home after work or on the weekends and holidays. This can solve one of the main problems of home deliveries, the high degree of failed deliveries due to the customers not being at home. Failed deliveries lead to additional costs, kilometers and emissions, as the delivery has to be repeated or the shipment needs to be dropped off at a service point.

By offering additional on-demand services such as precise delivery windows at any time or returns processing, SADRs can also help increase customer satisfaction. Similarly, using state-of-the-art technology in the last-mile can lead to a higher willingness to pay and increased customer interest. In a highly competitive market, greater customer loyalty can be achieved through improved service offerings, flexibility, and usability [14].

The possibility of using SADRs to reduce the need for human delivery staff could solve another problem for CEP providers: the current shortage of skilled workers. A recent study shows how the demand for jobs in Germany is changing. In 2022, for the first time, warehousing, post and delivery, and goods handling were among the top three most sought-after occupations. The surge in online commerce since the coronavirus pandemic is likely to have contributed significantly. The demand for workers continues unabated. In 2022, one in every 24 job advertisements was in the “warehousing, postal and courier” occupational group [15]. This suggests that the need for skilled workers is great, but many of the advertised positions could not be filled. The use of fully automated SADRs may help solve this problem.

2.2. Challenges

A large number of current scientific papers deal with the use of ADRs for the last-mile. While the potential of SADRs is generally known and accepted, some publications take a more critical view of their use cases and challenges of application [6; 14; 16].

A major challenge for the use of SADRs is the different regulations and laws, depending on the planned location of deployment. The regulations for autonomous driving are still being worked on in many places and can change at very short notice. In addition, roads are primarily taken as the reference area, which means that the regulations for cycle paths and sidewalks continue to lack transparency and reliability. This situation is particularly evident in the USA, where some states allow robots to participate in road traffic and have adapted their state traffic laws accordingly, while individual cities and municipalities formulate their own traffic laws for robots. This then leads to a multitude of rules with changing and sometimes contradictory laws. [17; 18]

Furthermore, safety concerns and public acceptance remain as SADRs operating on pedestrian paths can pose a safety risk as they can endanger pedestrians and lead to congestion on sidewalks. SADRs can directly or indirectly restrict the freedom of movement of other road users, create potential sources of danger, and, as a result, contribute to conflicts on sidewalks with pedestrians or cyclists or conflicts with motorized road users when crossing intersections.

Technical development has come a long way in recent years, so Level-4 autonomous driving is no longer anything special for SADRs, although there are still fully remote-controlled operating scenarios. However, permanent access to public cellular networks, like the LTE network, is required for smooth delivery and remote monitoring in the event of problems. In the event of network difficulties, the SADR may not be able to complete the delivery process and should be manually positioned so that it is not considered an obstacle to traffic until the connection is restored. Depending on local laws, it is sometimes necessary for the robot to be permanently monitored by human personnel. Regarding the capabilities of SADRs, it is clear that they are unable to overcome significant barriers such as stairs or ring a doorbell. As a result, recipients on higher floors in urban areas cannot be delivered directly to their apartment's front door, and recipients, in general, are dependent on additional technology, such as their smartphone, to be notified of the delivery and to open the SADR compartment to pick up their package.

Another disadvantage is that SADRs have a relatively small load volume, especially compared to standard delivery vehicles. Their payload capacity may not be suitable for delivering large or heavy items, which limits their application in some delivery scenarios.

One of the biggest concerns that potential customers have expressed relates to vandalism and theft. Customers are asking how the SADRs are protected against these and who covers the costs and insurance. However, it should be noted that SADRs are too heavy and unwieldy to be simply picked up. Their integrated cameras are able to monitor and record the entire environment while their GPS indicates the exact location. [19]

These last few points are, however, also one of the biggest challenges and criticisms of SADRs. Their constant data gathering and processing during their operations raises concerns about data security and privacy. Images, sound recordings, and films are used by the delivery robots for navigation, proof of delivery, and as evidence in the event of theft or accidents. This material is collected in public spaces and inevitably also contains image and sound data about (uninvolved) persons in the vicinity of the robots. In Europe, all these data fall under the European General Data Protection Regulation and must be protected from potential data misuse. [17]

3. Current SADR Projects / Applications for Parcel Delivery

In 2019, Baum et al. [9] identified 19 different SADRs that were in development, trials, or already applied. Of these, nine could be fully or partially assigned to parcel delivery, while the remaining robots could be assigned to food and supermarket delivery or were still at such an early stage of development that an assignment was not possible. As the SADR market is very fast-moving, new ideas are constantly emerging, new startups are being founded, and existing developments and companies are disappearing from the market or being taken over by competitors. For this reason, the following sections will first examine the current status of the nine robots or projects identified by Baum et al. before presenting further robots identified through a targeted search in publicly available publications and a structured internet search.

3.1. Status of Previously Identified SADR Projects

To say that the SADR market is very fast-moving is perhaps an understatement. Of the nine robots/projects identified by Baum et al., only two are still on the market for SADR; see Table II.

The robots or projects called Aida, AUS Post Robot, Eliport, and Sidewalk have since disappeared from the market or at least from the press, and their current status can be described as unknown. Dispatch was acquired by Amazon and a new robot called Scout was developed. However, Amazon stopped the project in 2022 [20]. The SADR developed by JD.com and its subdivisions/partners (mainly Dada Nexus Ltd.) is primarily applied for food and grocery deliveries [21]. They started with pilot projects for university campus delivery but switched to larger road-based vehicles for deliveries in public city areas [22], becoming the first company to apply Level-4 autonomous driving technology on public roads, according to their record [23]. In 2023, Cainiao Network Technology Co., the logistics division of Alibaba Group, took over the DAMO Academy, which was mainly responsible for developing autonomous delivery robots. DAMO Academy developed larger robots for street use before it was announced that 70 percent of the staff had been laid off, and research into autonomous delivery robots had been significantly postponed in the course of the integration [24]. TeleRetail developed a Level-5 self-driving robot for street and bicycle lane use. They also partnered with companies like Coca-Cola and ThyssenKrupp and tested the delivery of spare parts within urban environments and the delivery of parcels and documents on industrial sites [25]. It seems that SADRs for parcel delivery to end customers are not currently a priority research objective. Starship Technologies deployed its SADRs in various locations, partnering with businesses, universities, and municipalities to provide on-demand delivery services. They collaborate with food delivery services, grocery stores, and restaurants. In 2016, they started a pilot with Hermes for parcel delivery in Germany, which resulted in about 600 trips with around 3500 km [26]. The same year, they also partnered with Mercedes Benz Vans for combined van-robot parcel deliveries. However, no new information about parcel deliveries could be found since then. In 2022, Starship partnered with Co-op to deliver groceries to customers in the UK [27].

Table II.

Status of previously identified SADR

Project/Robot	***Company***	***Status***	***Last information***
Aida	-	unknown	None
AUS Post Robot	AUS Post	unknown	2019
Caniao G Plus/little G	Alibaba	switched to larger vehicles on roads, laid of 70 percent of staff	2023
Dispatch / Carry	Dispatch	acquired by amazon in 2017, new robot called Scout in 2019, Scout cancelled by amazon in 2023	2023
Eliport	Eliport	unknown	2020
JDrover	JD.com	switched to larger vehicles for parcel deliveries on roads	2023
Sidewalk	Sidewalk	unknown	2018
Starship	Starship Technologies	focussed mainly on food and grocery deliveries	2023
TeleRetail	TeleRetail	slightly larger vehicles on roads and bicycle paths	2021

3.2. Current SADR Projects

This section will now look into current SADR projects and point out those that are or have been used for parcel deliveries. The research shows that numerous multinational companies, startups, and international research groups focus on autonomous delivery robots. However, research into current SADR projects and applications found a handful of projects and companies that either no longer exist or have shifted their focus from sidewalk delivery to roads or other terrain [cf. Section 3.1.]. Those companies that could be identified developing or operating SADRs are mainly focused on food and grocery deliveries and, in addition, often apply their services in controlled environments such as college campuses. These companies are listed below in alphabetical order. The list is not exhaustive.

- Cartken: Partnered with Uber Eats to deliver food in Miami in 2022 [28]. Delivers food on college campuses in cooperation with Grubhub [29].
- KiwiBot: Partnered with Sodexo for food deliveries on US college campuses. Kiwibots' SADRs use Level 4 autonomy. Their robots are designed to operate on sidewalks, but their autonomy may be limited in areas with heavy pedestrian traffic or complex terrain [30].
- Neubility: They deploy their SADR "Neubie" for food, grocery, and retail deliveries, partnering with 7-Eleven. They deliberately refrain from using LiDAR in their robot to reduce costs [31].
- Ottonomy: Partnered with Goggo Network for food and retail deliveries in Spain in 2023. Ottonomy's first application was in the airport area, where the robots transported retail and food deliveries [32].
- Segway Robotics: Partnered up with Coco Delivery and DriveU.auto to develop and apply last-mile delivery robots. While Segway Robotics develops the robots, DriveU.auto is responsible for the software side of teleoperations, and Coco Delivery provides the food delivery services [33; 34].
- Serve Robotics: An autonomous sidewalk delivery robot startup backed up by Uber and Nvidia. They have a commercial agreement with Uber Eats to deploy up to two thousand Serve Robots in multiple markets across the United States [35].
- Yandex: They applied their SADRs for food delivery in three Russian cities and on US campuses, partnering up with GrubHub. They also started offering services for the Russian Post, delivering parcels from 27 post offices in Moscow in 2021. A total of 36 SADRs were to be deployed, resulting in one or two per post office. Customers were able to request delivery by SADR through a mobile application actively. While the package was being transported, customers could track the robot's location in the app and were notified by push notification or SMS upon arrival. This notification included a code to open the compartment and collect the shipment [36].

4. Conclusions

From a general perspective, it can be said that the use of robots for last-mile delivery is still in its infancy and is being driven forward by a number of pilot projects. The use of SADRs for parcel delivery looked promising in the years 2016 to 2018. However, only little has remained of this. With the exception of individual pilot projects and, most recently, the use of Yandex' robots for the Russian Post, there are currently no significant use cases. Most use cases are in the area of food deliveries. In addition to food delivery, limited, controllable environmental zones such as corporate premises or university campuses seem to be the focus of current projects. The advantage of these zones is a more controllable environment than public roads, for example, in terms of the complexity of public infrastructure, traffic, and congestion. The use of SADRs appears to be particularly worthwhile here and could become established in the coming years. The biggest challenge for the application of SADRs in urban areas and public spaces is not technical development but legal regulations.

The biggest opportunity for SADRs is the shortage of skilled workers. It is foreseeable that there will not be enough staff for delivery tasks in the future, or at least the delivery companies will not pay the required wages. SADRs can relieve the workload of the remaining workforce and provide useful support, relieving employees of unproductive routine activities.

In summary, it can be said that SADRs for parcel delivery can currently only be seen as an admixture for additional services such as on-demand and off-hour deliveries. At present, SADRs cannot deliver on the promise of reducing pollution and congestion in urban areas. Especially in parcel delivery, their application is not wide enough, and in the area of food delivery, it can be assumed that SADRs will either cause additional trips or, for the most part, replace bicycles rather than trucks. They can, however, serve as a supplement to relieve staff due to a shortage of skilled workers, but only with a very high degree of automation (at least Level-4) and without permanent additional human control and monitoring.

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