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Micromobility and micro-vehicles – A means to transform urban mobility and logistics?

Micromovilidad y microvehículos: un medio para transformar la movilidad urbana y la logística?

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Abstract:

Urban transportation systems worldwide are grappling with the imperative of achieving carbon neutrality by 2050. Currently, two primary strategies are being pursued. The first involves the adoption of novel, carbon-neutral energy sources such as electricity and hydrogen. The second strategy emphasizes the promotion of public transportation and active modes of commuting. A third, increasingly prominent approach is micromobility, which involves the use of compact electric vehicles spanning from electric-assisted bicycles to e-scooters and motorbikes, intended to supplant conventional car and fleet vehicle trips. A recent study conducted by Brost et al. (2022) demonstrated that more than 75% of total travel kilometers can be covered by micro-vehicles, contributing to a substantial 44% reduction in CO_2 emissions.

This paper will commence by conducting an in-depth exploration of the current landscape of micro-vehicles and their utilization, drawing from a comprehensive review of literature and market analysis. It will then proceed to establish a robust taxonomy of these vehicles and outline their present and potential applications. Subsequently, the paper will delve into the evolving trends in automated and autonomous driving functionalities within this

specific market segment. Additionally, it will elucidate cutting-edge research projects undertaken at the University of Magdeburg, namely AuRa and AuRa-Hirn.

Keywords: autonomous driving, micro-vehicle, mobility, sustainable mobility, urban logistics

Palabras Claves: conducción autónoma, microvehículo, movilidad, movilidad sostenible, logística urbana

1. Introduction

A paramount concern for nations across the globe revolves around the dual challenge of wealth preservation and environmental conservation, with the latter serving as the bedrock for a sustainable world. A pivotal avenue in addressing this challenge is the battle against human-induced climate change. The Paris Agreement, a landmark international accord, stipulates the imperative to limit global warming to below 1.5°C by 2050, aiming to minimize adverse planetary impacts (United Nations, 2015).to preserve the environment and its ecosystems as foundation of a livable world. One major approach here is to fight human made climate change. Within the Paris Agreement, it was internationally agreed upon, that global warming until 2050 should be kept below 1.5°C to keep effects on the planet as limited as possible (United Nations, 2015).

Transportation stands as a significant contributor to greenhouse gas (GHG) emissions, primarily in the form of carbon dioxide (CO_2), on a global scale. Road transport alone accounts for 11.9% of the total emissions, with transportation at large contributing 16.2% of global CO_2 emissions in 2016 (Ritchie et al., 2020). In industrialized nations, transportation's share of total GHG emissions is even more substantial. Domestic transport, excluding international shipping and aviation, shoulders approximately 23% of the total GHG emissions burden (European Environment Agency, 2023). Notably, cars and light-duty vehicles alone constitute 15% of this equation (European Council, 2023). Despite witnessing a general trend of decreasing GHG emissions in Europe, certain countries, such as Germany, persistently struggle to curtail emissions within the transport sector.

The transportation sector finds itself at an urgent juncture, necessitating the exploration and deployment of sustainable solutions. Considerable efforts are underway to transition from combustion engines to electric propulsion, shift transportation modes from roads to railways, and promote active mobility options like walking and cycling within cities and urban centers. A complementary approach, synergistic with the promotion of active mobility, involves fostering the adoption of micromobility. The term "micromobility" encompasses all forms of travel conducted with micro-vehicles, including e-scooters, e-bikes, cargo bikes, and light electric vehicles (LEVs) classified within the L-vehicle category (EU No. 168/2013). These vehicles have the potential to substitute for 76% of trips typically undertaken by conventional cars, resulting in a remarkable 44% reduction in GHG emissions (Brost et al., 2022).

Autonomous vehicles are advertised by the automotive industry as another solution to decrease carbon dioxide emissions. However, the prospective effects are challenged by several academics (Fraedrich et al., 2017; Hörl et al., 2019; Hardman et al., 2022) which claim, that those vehicles actually would increase mileage and therefore energy consumption also leading to more CO_2-emissions. However, automated and autonomous driving can improve the ease of mobility, the amenities and safety. Purely rejecting automated and autonomous driving won`t work. The better approach is to use this technology to make micro-vehicles a more attractive means of transport to motivate people to switch from cars to smaller, more sustainable vehicles. Despite the strong focus on the development of autonomous vehicles in the sense of a car (Assmann et al., 2020) the concept of automated and autonomous micro-vehicles is gaining momentum. Bike sharing systems with automated bikes can increase the sustainability of sharing (Sanchez et al., 2022). Baum et al. (2019) even predicted, that those vehicles will hit the streets sooner than cars and trucks. One promising field of application are last mile two-tier delivery systems (Engesser et al., 2023).

The contribution of this paper is a profound overview on the status quo of automated and autonomous micro vehicle development within mobility and logistics. It will display potential and current fields of application, know actors and technical parameters. The remainder of the paper structures as follows. Section 2 will briefly describe the methodology. In section 3 we will describe the status quo and shed a light on two case studies in the following section. Finally, section 5 will provide a discussion and final conclusion.

2. Methodology

This paper builds upon structured research encompassing grey literature and internet resources conducted by Baum et al. in 2019. Notably, one of the authors of this paper also contributed to the previous research. The earlier study established a systematic classification of automated and autonomous micro-vehicles, their potential application areas, and identified relevant companies and vehicle models. The current paper updates these findings by meticulously examining current data. Furthermore, we conducted additional structured research within the domain of grey literature and internet sources to uncover new vehicle types, companies, and application fields.

3. Results and Discussion

The field of automated micromobility and micro-vehicles is very heterogenous. This section will present the facets in terms of designated infrastructure, vehicle sizes and transport capabilities, the development status and will describe the fields of application to provide a sound overview.

3.1 Infrastructure and Operational Design Domain

The operational design domain (ODD) encompasses a set of operating conditions defining when an automated vehicle, ranging from SAE Level 1 to 4 automation, can operate without human intervention. Key attributes of an ODD include permissible infrastructure, speed limits, and environmental conditions, such as weather.

In the domain of automated micro-vehicles, we observe a broad spectrum of permissible infrastructure. Unlike the focused development of autonomous cars and trucks, which primarily operate on roads, micro-vehicles utilize the entire spectrum of street infrastructure, including cycling paths and sidewalks. (Figure 1).

Infrastructure delineates the permissible traffic and vehicle types, with sidewalks designated for pedestrians, wheelchairs, and other slow-moving, vulnerable users. Cycling paths, allowing higher speeds often limited by physical capabilities, provide a distinct domain for cyclists. These distinctions in speed and protection necessitate vehicle designs tailored to the safety of vulnerable street users, thus forming a foundational classification category.

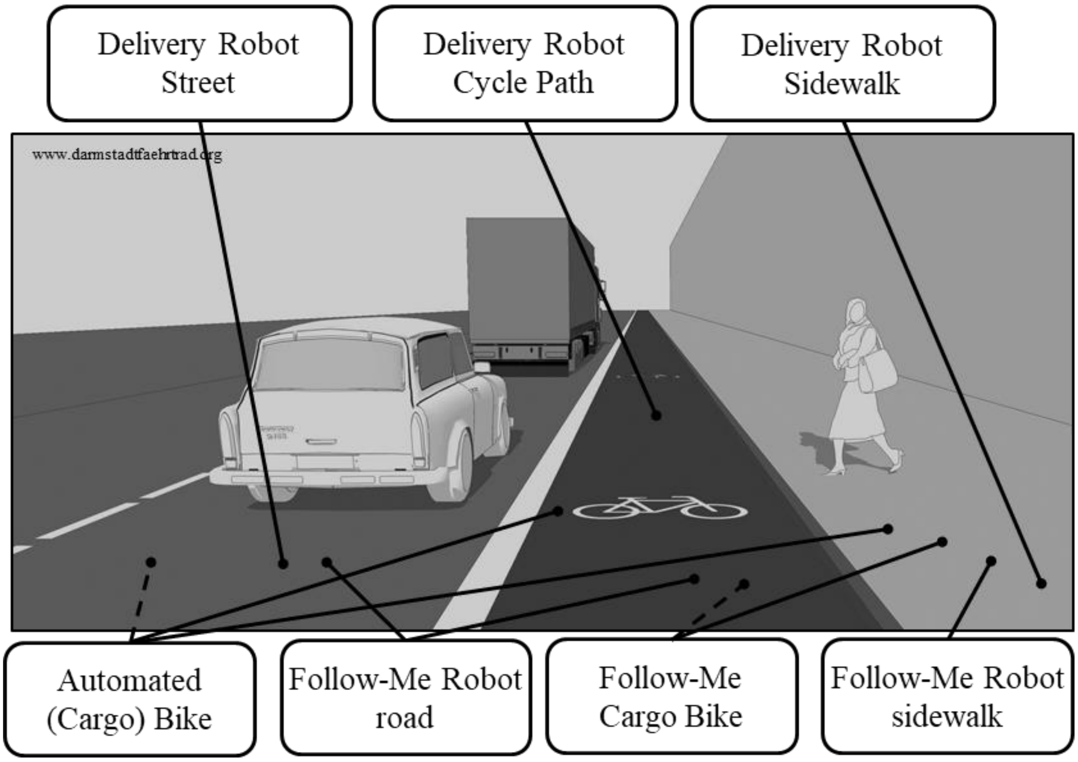

Figure 1: Infrastructure based classification of automated micro vehicles

3.2 Types of automated and autonomous micro-vehicles

Through our research, we've identified three primary classes of automated and autonomous micro-vehicles (Table 1). Delivery robots, geared towards logistics purposes, can operate on streets, cycling paths, and sidewalks. Robots and automated bikes find utility in both logistics and mobility applications.

In a subsequent analysis, we recognized the need for subclasses to better capture the diversity within each class. Within the delivery robot class, distinctions arise based on design and infrastructure utilization. Robots are known for "follow me" concepts, operating on cycle lanes, roads, or sidewalks. Bikes, conversely, vary more in terms of autonomous driving capabilities, with "follow me" approaches well-suited to sidewalks and fully autonomous bikes better suited to cycling paths and roads.

Table 1: Classification of automated micro-vehicles

Class	Subclass	Example
Delivery robot	Delivery Robot Street	https://clevon.com/
	Delivery Robot Cycle Path	https://heytheo.co/
	Delivery Robot Sidewalk	https://www.starship.xyz/
Robot	Follow-Me Cycle path	Ducktrain.io
	Follow-Me sidwalk	https://piaggiofastforward.com/
Automated Bike	Follow-Me cargo bike	https://www.aura.ovgu.de/Projekte/ EAASY+System.html
	Automated cargo bike	https://www.media.mit.edu/projects/ AutonomousBicycleProject/overview/

Although (Kondor et al., 2022) describe and investigate scooter sharing schemes with automated scooters, we could not find serious projects and companies following this approach.

3.3 Characteristics

Data pertaining to vehicle design parameters reveals significant differences among the introduced classes (Table 2). Road-based vehicles can achieve high speeds and boast payload capacities that rival current light-duty vehicles. Smaller designs are apparent for vehicles intended for cycling paths, often constrained to payloads around 300kg. Sidewalk vehicles, being the smallest, typically carry limited payloads, often equivalent to a shopping bag or a pizza box. These distinctions in speed and payload stem from the need to ensure the safety of pedestrians and cyclists, given their vulnerability in the event of an accident.

Delivery robots, as the name implies, are primarily dedicated to logistics purposes, whereas both bikes and robots find roles in logistics and mobility applications.

Table 2: Characteristics of automated micro-vehicles

Class	**Subclass**	**Speed (intended)**	**Domain**	**Payload**
Delivery robot	Delivery Robot Street	29-112,5 km/h	Logistics	35-2.500 kg
	Delivery Robot Cycle Path	20km/h	Logistics	20-100 kg
	Delivery Robot Sidewalk	3-12 km/h	Logistics	9-80 kg
Robot	Follow-Me cycling path	6 km/h	Mobility	10kg
	Follow-Me sidwalk	25-30km/h	Logistics	300kg
Bike	Follow-Me cargo bike	6km/h	Logistics	200kg
	Automated cargo bike	3-25 km/h	Mobility	24-150 kg

3.4 Technology Readiness

Evaluating the readiness of automated vehicles is a complex endeavor. Many companies claim to be operational or in pilot phases, making it challenging to ascertain the extent of automation and operational viability. Additionally, discerning whether a vehicle is genuinely automated or predominantly remote-controlled poses challenges. Our assessment relied on self-statements from companies through press releases and website content.

It is noteworthy that some companies have successfully deployed vehicles at numerous locations, with delivery robots prominently leading in real-world operations (Table 3).

Table 3: Technology Readiness of automated micro-vehicles

Class	**Subclass**	**Status**	**Company OR Product (Institution)**
Delivery robot	Delivery Robot Street	In operation	Nuro
		Trial	Clevon, Udelv, Loxo, TeleRetail
	Delivery Robot Cycle Path & closed premises	In operation	Alibaba
		Trial	Theo (Theo Robotics, status unclear);
	Delivery Robot Sidewalk	Operation	Starship, Kiwibot; Cartken, Coco, Segway, Serve, Neubility, Yape, Pika (Bizero), Yandex, ZMP
		Trial	Daxbot; Ottonomy, Tinymile, delivers.AI
		R&D	urbAnt (RWTH Aachen);
Robot	Follow-Me sidewalk	In Operation	Gita (Piaggio fast forward)
	Follow-Me street	R&D	Ducktrain (bankrupt)
Bike	Follow-Me cargo bike	Trial	
		R&D	AuRa (University Magdeburg), Helios (IAV, FZI),
	Automated cargo bike	R&D	Massachusetts Institute of Technology; AuRa (University Magdeburg), Velo Autonomous, WEEL, Huawai

3.5 Applications and Business Models

In the course of our research, we explored both current and potential fields of application and the corresponding business models. Notably, a predominant trend among companies is to adopt a service-oriented model, primarily centered around logistics-as-a-service. In this model, the company or its subsidiary retains ownership of the automated micro-vehicles and operates them. Revenue streams are typically generated per service rendered, with charges borne by either the recipient or, more commonly, the sender or premise operator.

A subset of companies seeks to generate revenue through vehicle sales. For companies in the research and development phase, determining a concrete business model remains challenging.

Delivery robots, with their advanced operational status, are employed across various applications, including:

- Grocery and food deliveries on university campuses.
- Food deliveries within enclosed premises such as airports and hospitals.
- Grocery and food deliveries in urban areas.
- Parcel deliveries in urban environments.
- Deployment as security bots within closed premises and urban settings.

Sidewalk robots are typically utilized for direct one-to-one deliveries, where goods are sent directly from the sender (e.g., retailer, restaurant, logistics hub) to the recipient. In contrast, delivery robots operating on cycling paths and roads, given their larger size, facilitate the consolidation of deliveries, making them suitable for parcel delivery services and transportation within densely populated urban areas with high demand for grocery and food deliveries. However, operational systems for road-based robots appear less common, likely due to the heightened safety requirements for autonomous robots on public roads.

Follow-me robots serve as assistants to humans, designed either to enhance personal mobility by transporting goods or to assist professionals. An intriguing use case for autonomous bikes lies in bike-sharing systems, which can enhance operational efficiency.

Additionally, it is interesting to note that companies tend to concentrate their operations in specific regions. The majority of companies are focused on North America and Europe, with a handful concentrating on markets in Russia, China, Japan, and South Korea. It's important to acknowledge that data pertaining to these markets might be limited, particularly in non-English languages, and may introduce a bias towards North America and Europe.

3.7 Spotlight: Automated and autonomous bicycles

Automated and autonomous bicycles might not be familiar to most professionals. To provide deeper insights into this concept and its intended effects, we spotlight two approaches:

For urban deliveries, a persistent challenge remains: How to provide doorstep deliveries to customers seeking convenience? In this regard, automated cargo bikes offer an intriguing solution. These bikes seamlessly switch between manual and automated driving modes, known as the "come-with-me" function (CWM).

During actual deliveries, the delivery person can activate the CWM mode, optimizing efficiency when making multiple stops in densely populated urban areas. In CWM mode, the cargo bike can autonomously follow the delivery person, drive in parallel, or park in secure spaces, all controlled via voice commands. This minimizes idle time for the delivery person, potentially increasing tour efficiency by 20%.

Within the AuRa research project, an on-demand self-driving cargo bike service is under development. This system leverages autonomous driving capabilities to enable automated, demand-responsive rebalancing, reducing effort and service disruptions. Users initiate requests for autonomous cargo bikes via a smartphone app. The operations control center (OCC) selects a suitable bike, which autonomously travels to the user's location. Upon arrival, the user manually rides the bike to their destination, after which the bike autonomously proceeds to the next customer or a waiting or charging station (Kania & Assmann, 2023).

4. Discussion and conclusions

Baum et al. (2019) conducted their research in 2018, with the paper published in 2019. This update, conducted in the summer of 2023, provides insights into five years of developments in the automated micro-vehicle sector.

Firstly, we observe a dynamic market landscape with notable changes in market actors. Nearly half of the sidewalk delivery robot companies that were actively making deliveries in 2018 no longer exist. They were either acquired or had to discontinue their development. Nonetheless, the market remains highly competitive, with six companies entering this market successfully within the last five years. It is essential to highlight that while sidewalks are used by many players, most operations occur in controlled environments such as university campuses.

A similar picture emerges in the realm of road-based delivery robots, albeit with fewer active companies. Importantly, only one company seems to be operational at this point.

In the robot and bike segments, the numbers are too limited to draw definitive conclusions. Nevertheless, the presence of new entrants signals anticipated growth in these areas. Currently, only one company has its product commercially available. Future updates will need to consider whether automated scooter schemes have gained momentum, potentially warranting their classification as a distinct category.

Baum et al. (2019) proposed the hypothesis that automated micro-vehicles might hit the streets ahead of fully autonomous cars. Given the limited deployment of fully autonomous car fleets and the widespread use of autonomous delivery robots, this prediction appears valid. However, it's important to note that further investigation is required to determine the extent of autonomy in delivery robot operations. Data limitations make it challenging to establish definitively whether these robots operate autonomously or rely heavily on remote control.

To this point we can conclude, that automated micro-vehicles are out there in operation and are likely to expand the business, espacially in the logistics field. First investigations suggest, that those vehicles can improve sustainability of urban transport systems. However, we do not know the extend and if they will start a transformation of urban transport or if they will stay in small niches.

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