Emerging Automated Urban Freight Delivery Concepts:

State of the Practice Scan

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16. Abstract

Due to the growing interest in automated urban freight delivery and the multimodal nature of the topic, the Intelligent Transportation Systems Joint Program Office partnered with the USDOT John A. Volpe National Transportation Systems Center to produce this "Emerging Automated Urban Freight Delivery Concepts: State of the Practice Scan" report. Based on a review of literature, monitoring information on testing activity, and engagement with industry stakeholders, this report characterizes the state of the industry (e.g., motivations, actors, activities, current issues, and mitigation strategies) in order to improve understanding of these automated delivery vehicle concepts and industry activities, identify emerging issues, and present objective findings to stakeholders.

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Table of Contents

List of Figures

List of Tables

Abbreviations

3-D – Three-dimensional

AAA – American Automobile Association

ADA – Americans with Disabilities Act

ADAS – Advanced driver assistance systems

ADS – Automated driving systems

DDT – Dynamic driving task

FAA – Federal Aviation Administration

FHWA – Federal Highway Administration

FMCSA – Federal Motor Carrier Safety Administration

FMVSS – Federal Motor Vehicle Safety Standards

FTA – Federal Transit Administration

GNSS – Global Navigation Satellite Systems

HD Maps – High-definition maps

HMI – Human-machine interface

IMU – Inertial measurement unit

ISO – International Organization for Standardization

ITS JPO – Intelligent Transportation Systems Joint Program Office

LSV – Low-speed vehicle

MARAD – Maritime Administration

MPH – Miles per hour

NHTSA – National Highway Traffic Safety Administration

ODD – Operating design domain

OSHA – Occupational Safety and Health Administration

PDD – Personal delivery device

SAE – An SDO formerly known as the Society of Automotive Engineers

SDO – Standards development organization

TNC – Transportation network company

UAS – Unmanned aircraft systems

USDOT – U.S. Department of Transportation

VSSA – Voluntary Safety Self-Assessments

Volpe Center – John A. Volpe National Transportation Systems Center

Chapter 1. Introduction

Automated urban freight delivery is attracting interest from industry, new concepts are emerging, and companies are testing in increasingly realistic environments. The topic has potential implications for multiple operating administrations within the U.S. Department of Transportation (USDOT), including the Federal Highway Administration (FHWA), the Federal Motor Carrier Safety Administration (FMCSA), the Federal Transit Administration (FTA), the Maritime Administration (MARAD), and the National Highway Traffic Safety Administration (NHTSA). Because of the growing interest and the multimodal nature of the topic, the Intelligent Transportation Systems Joint Program Office (ITS JPO) partnered with the USDOT John A. Volpe National Transportation Systems Center (Volpe Center) on the “Emerging Automated Urban Freight Delivery Vehicle Concepts” project. The purpose of this State of the Practice Scan is to characterize the state of the industry (e.g., motivations, actors, activities, current issues, and mitigation strategies) in order to improve understanding of these automated delivery vehicle concepts and industry activities, identify emerging issues, and present objective findings to stakeholders.

Report Scope

This report addresses a variety of different automated delivery vehicle concepts ranging from small delivery robots to light- and medium-duty vehicles. It considers a variety of operating environments (e.g., on sidewalks or on private or public roads), vehicle speeds, and service models (e.g., home delivery, mobile storage lockers, and roving retail stores). Similarly, the scope covers different phases of delivery, including the “final-50-feet” to a customer’s door, the “last-mile” to the curb at an address, and “middle-mile” deliveries from warehouses to commercial locations.[1]

Several delivery concepts using automation or remote monitoring and operation were considered outside of the scope of this report. For example, automated commercial motor vehicles operating on highways have been relatively well studied by others and were not evaluated here. Similarly, vehicles that operate exclusively in closed environments (e.g., indoors at hotels or office buildings, on warehouse or factory floors, or on airport tarmacs) were not included, since they operate outside the national transportation system. Out-of-scope concepts (including heavy-duty commercial trucks, unmanned aircraft systems, indoor robots, airport baggage tractors, and underground delivery systems) are described in more detail in Appendix A.

Level of automation is another relevant factor with respect to the scope of this research. SAE International (formerly known as the Society of Automotive Engineers), a standards development

[1] The term “final-50-feet” is commonly used to refer to bringing packages from the road to the recipient’s front door (“final” is sometimes replaced with “last” and “50” is sometimes replaced with “100” or “10” when referring to this delivery phase). While some automated delivery vehicles are designed to provide this level of service, not all of them include this capability.

organization (SDO), has defined different levels of driving automation systems.[2] At the lower end of the spectrum are advanced driver assistance systems (ADAS), which include features with no automation component (e.g., warnings and alerts), as well as features that automate aspects of braking, acceleration, and steering.[3] These lower-level automation features require a fully engaged and attentive human driver to constantly supervise the operation of the vehicle and monitor its surrounding environment; that driver must be able to maintain control of the vehicle.

At the other end of the automation spectrum are Automated Driving Systems (ADS – SAE Automation Levels 3-5), where the system is able to control both the driving and monitoring tasks within its operating design domain (ODD). Specifically, the systems of interest for this report are considered by their manufacturers to be SAE Level 4, which means that no human driver is needed as long as the vehicle is within its ODD. It is worth noting that many of the relevant automated delivery vehicle concepts are designed with the eventual intent of using SAE Level 4 systems, but many of the developers of the vehicles in the prototype and testing stage currently use manual supervision and intervention (either on-board the vehicle with an attendant or from a remote location).

Methodology

The findings identified in this report are based on a mixed methodology that includes a review of literature on automated delivery vehicles and related topics; monitoring information on international and domestic testing activity and vehicle concepts; and engagement with industry stakeholders.

- **Literature reviews** of several topics including testing and deployment, public sentiment and acceptance, safety, remote monitoring and teleoperations, policy and regulation, security, equity, network impacts, and other issues. Literature reviews included existing transportation databases, academic sources, and references in the news media.
- **Test and concept monitoring** included the aggregation of information on international and domestic automated delivery vehicle testing through a review of media reporting, company websites, and other publicly available materials. The tracking effort also included gathering information on theoretical or emerging concepts, where there was no public testing or demonstration.
- **Stakeholder engagement** primarily focused on telephone interviews with automated delivery vehicle developers, academics, and government officials, but it also included in-person conversations with representatives at conferences and trade shows (see Appendix C for a full list of interviewees). The project team also conducted site visits and participated in demonstrations.

[2] See Appendix B for additional information on the SAE levels of driving automation. SAE. (2018). “Taxonomy and Definitions for Terms Related to Driving Automation Systems for On-Road Motor Vehicles” SAE International. June 15, 2018. <https://www.sae.org/standards/content/j3016_201806/>.

[3] AAA, Consumer Reports, J.D. Power, and NSC. (2019). “Clearing the Confusion: Recommended Common Naming for Advanced Driver Assistance Technologies” Consumer Reports website. October 18, 2019. <https://advocacy.consumerreports.org/wp-content/uploads/2019/11/CR-ADAS-Common-Naming-One-pager.pdf>.

Objectives

This report aims to document information on the rapidly evolving state of the practice with respect to automated delivery vehicles to inform USDOT engagement in this area. To achieve these goals, this report seeks to identify the range of concepts, provide an overview of some participants and testing activities, and document common issues and research priorities associated with automated delivery vehicles.

Disclaimer

Note that this report is not intended to be comprehensive—information on companies and activities is meant to give a sense of current activities related to the development and testing of automated delivery vehicles. Company and product names referenced in this report are included only for illustrative purposes and do not represent an endorsement.

Document Organization

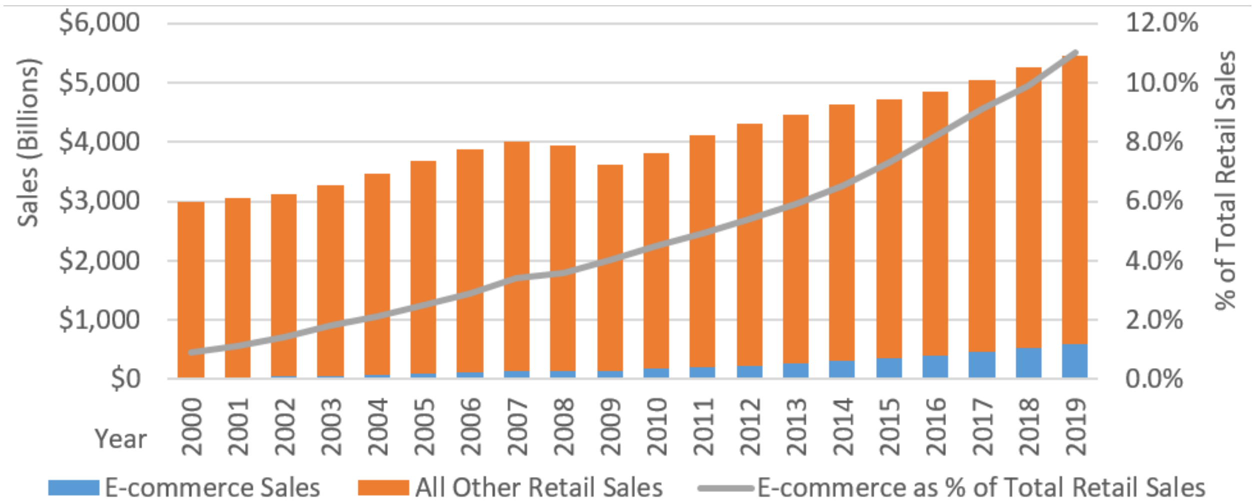
Chapter 2 describes various related trends and automated delivery vehicle concepts with examples of each. Chapter 3 discusses the industry in terms of various private-sector roles and testing activity as well as discusses foundational ADS technologies and concepts. Chapter 4 provides context relevant Federal, State, and local policies and regulations, Chapter 5 discusses potential network impacts from automated delivery vehicles, and Chapter 6 discusses other testing and deployment considerations. Chapter 7 highlights conclusions and key findings.

Chapter 2. Automated Delivery Vehicles

This chapter discusses broad trends related to increased delivery activity, the increased use of automation in delivery, and an overview of emerging automated delivery vehicle concepts. The chapter also includes information on foundational technologies that enable ADS and operating environments for ADS-equipped vehicles.

Delivery Trends

Changes in consumer behavior are altering the retail and delivery industries, and along with them, traffic patterns and curb space usage. A growing number of consumers are using online ordering and delivery for more items, from books and electronics to clothing and food. There has been growth in traditional restaurant deliveries, and food delivery services have expanded to include meal kits and groceries.[4]



Note: Annual estimates are unadjusted and are based on data from the Monthly Retail Trade Survey and administrative records.
Source: Census 2020

Figure 1. Chart of U.S. Retail Sales 2000-2018

The number of packages arriving at front doors has increased in both volume and velocity. Walmart recently made its same-day-delivery option available for 75 percent of the population of the United States,

[4] Cheng, A. (2018). “Millennials Are Ordering More Food Delivery, But Are They Killing the Kitchen, Too?” Forbes. June 26, 2018. <https://www.forbes.com/sites/andriacheng/2018/06/26/millennials-are-ordering-food-for-delivery-more-but-are-they-killing-the-kitchen-too/#48b5251d393e>.

while Amazon already delivers to nearly three-quarters of their customers within 24 hours.[5] Same-day and even same-hour delivery have become the new normal,[6] resulting in more frequent but smaller packages, sometimes delivered on smaller vehicles.[7]

As shown in Figure 1, e-commerce sales (i.e., online purchases) have increased from less than 1.0 percent of all retail sales in 2000 to 11.0 percent of all retail sales in 2019, with continued growth in the first quarter of 2020.[8] Excluding sales of items not normally purchased online (e.g., spending at restaurants, bars, and gas stations), online retail spending reached 16 percent of retail sales in 2019.[9] Since 2010, e-commerce sales have grown at an average annual rate of approximately 15 percent, but the COVID-19 public health emergency has at least temporarily accelerated the trend, with 146 percent year-over-year growth in online retail orders as of April 2020.[10] More online orders translate to more deliveries, more delivery vehicles, and more trips to pick up and drop off packages. These deliveries increasingly contribute to urban congestion and pollution, and World Economic Forum analysis suggests that those issues will continue to grow over the next decade.[11] Many cities are already concerned about the availability and use of curb space due to the rise of transportation network companies (TNCs), such as Uber and Lyft, and micromobility modes (e.g., shared e-bicycles and e-scooters), but the increased rates of delivery create their own curb space concerns.[12]

Stakeholders have indicated that last-mile delivery emissions, congestion, and road safety are growing concerns, and some are examining new models in response.[13] For example, the National Association of

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[5] WEF. (2020). "The Future of the Last-Mile Ecosystem." World Economic Forum. January 2020. <http://www3.weforum.org/docs/WEF_Future_of_the_last_mile_ecosystem.pdf>.

[6] Boyle, M. (2019). "Walmart Matches Amazon with One-Day Shipping on Many Items." Bloomberg. May 13, 2019. <https://www.bloomberg.com/news/articles/2019-05-14/walmart-matches-amazon-with-free-one-day-shipping-on-many-items>; Jones, C. (2019). "Amazon looking to shift to one-day Prime shipping and delivering orders wherever you want." USA Today. April 28, 2019. <https://www.usatoday.com/story/money/2019/04/25/amazon-delivers-7-eleven-coachella-your-car-woo-shoppers/3541178002/>; and Safdar, K. (2018). "Target Undercuts Amazon with Free Two-Day Shipping" Wall Street Journal. October 23, 2018. <https://www.wsj.com/articles/target-undercuts-amazon-with-free-two-day-shipping-1540326600>.

[7] This is referred to in logistics as "atomization," or moving toward the smallest load unit that can be effectively transported.

[8] Census. (2020). "Monthly Retail Trade - Latest Quarterly E-Commerce Report." US Census Bureau. May 19, 2020. <https://www.census.gov/retail/index.html#ecommerce>.

[9] Young, J. (2020) "US ecommerce sales grow 14.9% in 2019." Digital Commerce 360. February 19, 2020. <https://www.digitalcommerce360.com/article/us-ecommerce-sales/>.

[10] Columbus, L. (2020). "How COVID-19 Is Transforming E-Commerce." Forbes. April 28, 2020. <https://www.forbes.com/sites/louiscolumbus/2020/04/28/how-covid-19-is-transforming-e-commerce/#17fdf8ba3544>.

[11] Ibid. WEF. (2020).

[12] ITE. (2018). "Curbside Management Practitioners Guide." Institute of Transportation Engineers. November 15, 2018. <https://www.ite.org/pub/?id=C75A6B8B-E210-5EB3-F4A6-A2FDDA8AE4AA>.

[13] ITDP. (2019). "Urban Freight Will Keep Growing, but it Doesn't Have to Look Like This." Institute for Transportation and Development Policy. September 13, 2019. <https://www.itdp.org/2019/09/13/urban-freight-will-keep-growing-but-it-doesnt-have-to-look-like-this/>.

City Transportation Officials, which represents 81 major North American cities and transit agencies, calls for regulation and incentives to encourage companies to downsize their delivery platforms.[14] On the supply side, both established logistic firms and technology startups are exploring new delivery models. Many companies are using app-enabled platforms and contract employees to pick and deliver prepared food, groceries, and other retail items, creating entirely new supply chains that did not exist a decade ago. While many of these deliveries use vans or light-duty vehicles, other deliveries use smaller vehicles such as bicycles and scooters.

A number of other innovations have been identified, such as common carrier lockers, which could potentially allow for simplified and secure package access for dense neighborhoods without each carrier needing to separately deliver to each residential unit or building.[15] Urban consolidation centers could similarly help to reduce the number of last-mile delivery trips. The related solution of mobile hubs is increasingly used in cities such as New York, where large trucks are parked strategically early in the morning and then used as a mobile depot for the day.[16]

Together, these demand-side and supply-side trends represent both a challenge and an opportunity, as final delivery represents the most expensive stage in the process—according to Honeywell Sensing & Productivity Solutions, 53 percent of typical logistics costs are associated with last-mile delivery.[17] As a result, many companies are looking to automation and other technology solutions to help reduce costs associated with package delivery.

Automation in Delivery

Over the past several decades, automation has transformed factory floors, streamlining processes and improving precision, and driving increased productivity. While automation has been well suited for repetitive actions in highly controlled environments, it is used less frequently for processes in dynamic, unpredictable, and open environments. However, the rise in use of delivery services, combined with advances in automated vehicle technologies, is paving the way for the development of automated delivery vehicles.

Automation is increasingly used in the initial stages of delivery (e.g., selecting items and transporting inventory around the warehouse). The question of how automation can be used in the rest of the delivery

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[14] NACTO. (2020). “Blueprint for Autonomous Urbanism: Second Edition – Urban Freight” National Association of City Transportation Officials. Accessed June 18, 2020. <https://nacto.org/publication/bau2/urban-freight/>.

[15] Spector, S. (2020). “The Future of Urban Freight: The Latest Smart City Logistics Trends.” Supply Chain Transportation and Logistics Center at the University of Washington. January 2, 2020. <http://depts.washington.edu/sctlctr/news-events/in-the-news/future-urban-freight-latest-smart-city-logistics-trends>.

[16] Quirk, V. (2018). “Outside the box truck: Innovations in delivery that could change our cities.” Side Walk Talk on Medium. September 13, 2018. <https://medium.com/sidewalk-talk/outside-the-box-truck-innovations-in-delivery-that-could-change-our-cities-a7c2170d8f9b>.

[17] McCrea, B. (2019). “From DC to Final Destination: Last Mile Dilemma: The race is on to close the last mile delivery gap, cut costs and improve customer service.” Modern Materials Handling. June 8, 2016. <https://www.mmh.com/article/from_dc_to_final_destination_last_mile_dilemma>.

process—from intercity operations (long-haul) to intracity operations (short-haul) to final package delivery (final-50-feet) is an active area of research.

Many companies are investigating whether automated vehicles have the potential to serve as an alternative to the manual last-mile delivery of items. Retailers (e.g., CVS, Kroger, Stop & Shop, and Walmart), restaurants (e.g., Domino's), and shippers (e.g., FedEx and Amazon) are embracing technology in the form of sidewalk delivery robots, ADS-equipped vehicles, unmanned aircraft systems (UAS), and other novel technologies. On the technology development side, there is significant startup activity, but there are also entries from larger, established automakers (e.g., Ford, General Motors, and Toyota) and major automotive suppliers (e.g., Continental and ZF).

Industry has made substantial investments in the fledgling automated delivery vehicle industry, with McKinsey & Company estimating that automated delivery vehicles will account for approximately 80 percent of deliveries by 2025.[18] Research firm MarketsandMarkets has valued the automated delivery vehicle market at approximately $11.9 million in 2018 and it expects it to grow to $34.0 million by 2024 (19.2 percent annual growth).[19] Frost & Sullivan estimates the automated delivery vehicle market to be worth $16.8 billion by 2030.[20] A scenario analysis conducted by KPMG suggests that by 2040, the United States could require between 300,000 and 1.0 million automated delivery vehicles.[21] While these predictions may not be fully aligned with respect to addressing the same vehicle type (e.g., some may refer to smaller delivery robots that operate on sidewalks, while others may refer to larger automated delivery vehicles that operate on public roads), they illustrate the industry expectation that the area of automated freight delivery will see substantial growth in coming years.

Automated Delivery Vehicle Taxonomy

Currently, many different concepts exist for automated delivery. Vehicles range from smaller sidewalk delivery robots (both wheeled and legged models), to traditional light-duty vehicles (e.g., sedans and vans), to road-based vehicles with novel designs. Some companies have proposed combination models where multiple automated vehicle or robot devices would work together as a single delivery system.

While some analysts have attempted to segment automated delivery concepts using various characteristics, including vehicle type, weight, carrying capacity, speed, purpose/application/end-user, or

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[18] Joerss, M., Schröder, J., Neuhaus, F., Klink, C, and Mann, F. (2016). "Parcel Delivery: The future of last mile." McKinsey & Company. September 2016. <https://www.mckinsey.com/~/media/mckinsey/industries/travel%20transport%20and%20logistics/our%20insights/how%20customer%20demands%20are%20reshaping%20last%20mile%20delivery/parcel_delivery_the_future_of_last_mile.ashx>.

[19] Singh, S. (2019). "Delivery Robots Market worth $34.0 million by 2024." Markets and Markets Press Release. January 29, 2019. <https://www.marketsandmarkets.com/PressReleases/delivery-robot.asp>.

[20] F&S. (2018). "The Future of Last-mile Delivery Bots." Frost & Sullivan. April 16, 2018. <https://store.frost.com/the-future-of-last-mile-delivery-bots.html>.

[21] Silberg, G. (2019). "Autonomy Delivers: An Oncoming Revolution in the Movement of Goods." KPMG. March 2019. <https://advisory.kpmg.us/content/dam/advisory/en/pdfs/2018/autonomy-delivers-final-secured-web.pdf>.

other characteristics, such as number of wheels or sensor suite,[22] no definitive categorization exists.[23] Some descriptions, such as “sidewalk robots” or “sidewalk delivery robots,” have gained common usage in media coverage.[24] In previous automated vehicle reports, USDOT has used characteristics such as “conventional,” “advanced,” or “novel” design to describe different categories of automated vehicles.[25] In defining a taxonomy to describe in-scope and out-of-scope concepts for this research project, USDOT research staff considered classifications used in other reports, commonly used terms, and pre-established conventions.

For this report, the research team developed unofficial working definitions for the categories of automated urban freight delivery concepts considered to be within the scope of research. Note that these unofficial working definitions do not apply beyond the scope of this report. ‘Unofficial’ means that they have not been formally adopted for or approved by modal agencies within the Department. On the following page, Table 1 identifies different concepts that are described further in subsequent paragraphs with high-level information on each automated delivery vehicle category and examples of companies that are pursuing those concepts. Many companies are involved in the development and production of each category of automated delivery vehicle, with many examples listed in Appendix D.

[22] The term “sensor suite” refers to the mix of various sensors (e.g., type, number, and placement) on an automated vehicle. The Vehicle and Technology Limitations chapter contains more information on various sensor types commonly used in automated vehicles.

[23] Rubio, F. Valero, F. and Llopis-Albert, C. (2019). “A review of mobile robots: Concepts, methods, theoretical framework, and applications.” *International Journal of Advanced Robotic Systems*, 16(2):1-22 March-April 2019. <https://journals.sagepub.com/doi/pdf/10.1177/1729881419839596>; Ibid. Joerss et al. (2016); Marks, M. (2019). “Robots in space: Sharing our world with autonomous delivery vehicles.” Working paper, presented at We Robot. April 12, 2019. <https://robots.law.miami.edu/2019/wp-content/uploads/2019/04/Marks_Robots-in-Space.pdf>; Rothbard, S. (2019). “The Impact of Autonomous Vehicles on Last-Mile Delivery.” Sidewalk Labs. Presentation at Home Delivery World 2019—Seminar Theater Urban Logistics. Pennsylvania Convention Center, Philadelphia, PA. April 4, 2019; TMR. (2019). “Delivery Robots Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast 2018 – 2028.” TMR Research. July 2019. <https://www.tmrresearch.com/delivery-robots-market>; and Ghaffarzadeh, K. and Jiao, N. (2019). “Mobile Robots, Autonomous Vehicles, and Drones in Logistics, Warehousing, and Delivery 2020-2040.” IDTechEx Research. November 2019. <https://www.idtechex.com/en/research-report/mobile-robots-autonomous-vehicles-and-drones-in-logistics-warehousing-and-delivery-2020-2040/706>.

[24] Sidewalk delivery robots are also sometimes referred to as personal delivery devices (PDDs), especially in legislation and pilot programs created by local governments.

[25] Kim, A., Perlman, D, Bogard, D., and Harrington, R. (2016). “Review of Federal Motor Vehicle Safety Standards (FMVSS) for Automated Vehicles: Identifying potential barriers and challenges for the certification of automated vehicles using existing FMVSS.” U.S. Department of Transportation. March 2016. <https://rosap.ntl.bts.gov/view/dot/12260>.

Table 1. Automated Urban Freight Delivery Vehicle Concept Categories

Vehicle Category	Payload/Capacity	Operating Environment	Intended Delivery Phase
Wheeled sidewalk delivery robots	Small to medium (<100 lbs., <10 ft³)	Sidewalk and pedestrian paths	Final-50-feet or last-mile
Legged sidewalk delivery robots	Small to medium (<100 lbs., <10 ft³)	Sidewalk and pedestrian paths	Final-50-feet
Conventional design automated delivery vehicles	Medium to large (>100 lbs., >10 ft³)	Roadways (public or private)	Middle-mile or last-mile
Novel design automated delivery vehicles	Medium to large (>100 lbs., >10 ft³)	Roadways (public or private)	Middle-mile or last-mile
Combination automated delivery vehicle models	Medium to large (>100 lbs., >10 ft³) – depending on concept, larger payloads may need to be divided into multiple smaller packages	Roadways (public or private), Sidewalk and pedestrian paths (robot delivery), or low-altitude airspace (UAS delivery)	Last-mile and final-50-feet

Source: USDOT Volpe Center 2020

The roles of humans may also vary by vehicle category and stage of development. In many cases, service concepts require a human to be present to load and unload vehicles. If a staff member is present (e.g., an on-board attendant for larger vehicles or a chaperone for sidewalk delivery robots), that staff member may take on some of those roles. In other cases, recipients may need to be present to retrieve packages from the vehicle. Some combination automated delivery vehicle concepts envision the use of multiple automated systems to complete delivery without requiring a human to be present, though such a concept has yet to be tested beyond limited demonstrations.

Wheeled Sidewalk Delivery Robots

Wheeled sidewalk delivery robots vary with respect to design (e.g., sensor suite and number of wheels) and size (e.g., from a few cubic feet to several cubic feet), but overall, they can carry a medium to small payload and operate on sidewalks and other pedestrian areas. Climbing curbs or stairs may be possible, depending on the robot design. For delivery, these robots typically require a recipient to be present to open and unload the vehicle (i.e., most vehicles are incapable of discharging packages autonomously). These robots do not have space dedicated for an on-board operator, but they typically have systems for remote monitoring and operation.

Several wheeled sidewalk delivery robots have been deployed in pilots on university campuses. For instance, Robby Technologies partnered with Pepsi to operate vehicles with drinks and snacks at the

University of the Pacific.[26] Kiwi has launched food delivery pilots on the campuses of UC Berkeley and the University of Denver,[27] and Starship began operating pilots at multiple locations, including George Mason University, Northern Arizona University, University of Pittsburgh, and Purdue University.[28]

Legged Sidewalk Delivery Robots

As with their wheeled counterparts, legged sidewalk delivery robots vary with respect to design—most notably, some are bipedal (two legs) and some are quadrupedal (four legs). Like other sidewalk delivery robots, they can carry a medium to small payload and operate on sidewalks and other pedestrian areas. One of the major benefits of legged robots over wheeled robots is their ability to climb curbs and stairs. Some demonstrations have even shown robots using their legs to ring a doorbell.[29] In addition, depending on the design, legged robots may not need a recipient to be present to receive the package—these robots are typically designed to deposit packages by themselves, allowing them to leave items at a recipient's front door. These robots are not designed to accommodate an on-board operator, but they may rely on systems for remote monitoring and operation.

While legged robots may be able to overcome some of the limitations of their wheeled counterparts, they have some of their own challenges, including greater technological complexity and lower operating speeds.[30] These limitations may help explain why, to date, legged sidewalk delivery robots have not been deployed in pilots, although they have been featured at conference demonstrations and in concept videos. For instance, the ANYbotics "ANYmal" robot and the Agility Robotics "Digit" robot were demonstrated during the Consumer Electronics Show in 2019 and 2020, respectively.[31]

Conventional Design Automated Delivery Vehicles

Many companies are seeking to modify existing light-duty vehicle platforms, such as sedans or cargo vans, into automated delivery vehicles. The light-duty vehicle format is capable of carrying medium to large payloads (compared to smaller packages in sidewalk delivery robots). Typically, the base vehicles are designed to comply with Federal Motor Vehicle Safety Standards (FMVSS), which regulate the design, construction, performance, and durability of motor vehicles and equipment. In some cases, companies such as Boxbot and Udelv are using electric low-speed vehicles (LSV) that comply with

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[26] Pepsi. (2019). "PepsiCo's Hello Goodness snackbot is Off to College." Pepsi Press Release. January 3, 2019. <http://pepsico.mediaroom.com/index.php?s=43&item=1431>.

[27] Kane, W. (2018). "Those four-wheeled robots on campus, explained." Berkeley News. May 31, 2018. <https://news.berkeley.edu/2018/05/31/those-four-wheeled-robots-on-campus-explained/>.

[28] Hawkins, A. (2019). "Thousands of autonomous delivery robots are about to descend on US college campuses." The Verge. August 20, 2019. <https://www.theverge.com/2019/8/20/20812184/starship-delivery-robot-expansion-college-campus>.

[29] ANYbotics. (2019). "Robotic Package Delivery with ANYmal." ANYbotics AG Website. January 31, 2019. <https://www.anybotics.com/robotic-package-delivery-with-anymal/>.

[30] Niedermeyer, E. (2019). "Why Ford's Humanoid Robot Partnership Is More Than A Gimmick." The Drive. May 22, 2019. <https://www.thedrive.com/tech/28165/why-fords-humanoid-robot-partnership-is-more-than-a-gimmick>.

[31] Ibid. ANYbotics. (2019); and Ibid. Niedermeyer, E. (2019).

applicable FMVSS and may be slightly smaller than most light-duty vehicles (e.g., Polaris GEM vehicles).[32]

In addition to variations in the selection of the base vehicle, companies are using different sensor suites, human-machine interfaces (HMIs), and delivery models. These vehicles are designed to operate with SAE Level 4 automation, but because they use conventional vehicles, they have room for human passengers. Depending on the company's policies, they may include an on-board operator (often called a safety driver) in the driver's seat.

These vehicles cannot discharge packages without human assistance and require either the recipient to be present to open and unload the vehicle, or use of the on-board operator to complete that task. As an alternative to a human unloading the vehicle, some models are looking at using robots or small UAS to unload—those concepts are further discussed in the Combination Automated Delivery Vehicle Models section. One drawback of the larger vehicle format is the need for access to driveways or curb space. If the recipient is required to claim their package, the amount of time that the vehicle spends parked and waiting for the recipient to arrive could substantially increase vehicle dwell time (as compared to conventional delivery models where the driver carries the package to its recipient). As a result, services that use conventional design automated delivery vehicles could require more intensive use of curb space and contribute more to congestion than traditional delivery methods.

Many companies are using light-duty automated delivery vehicles with conventional designs to pilot delivery services for real customers. In August 2018, AutoX launched a pilot to deliver groceries to 400 homes in San Jose, CA in a modified Lincoln MKZ.[33] In January 2019, Cruise Automation announced that it would partner with DoorDash and use some of its automated Chevrolet Bolt fleet to deliver food in San Francisco, CA.[34] Ford has partnered with Dominos, Postmates, and Walmart to test delivery in Ann Arbor, MI and Miami, FL using Ford Fusion and Ford Transit Connect vehicles.[35] Gatik is also partnering with Walmart and is using a modified Ford Transit Connect to make middle-mile deliveries in Bentonville, AR.[36] In November 2018, ThorDrive began a pilot to deliver goods from an Ace Hardware store to a nearby community center in Palo Alto, CA.[37] Udelv had participated in multiple pilots in Arizona, California,

[32] NHTSA. (2006). "Federal Motor Vehicle Safety Standards - Low-Speed Vehicles." Federal Register. April 19, 2006. <https://www.federalregister.gov/documents/2006/04/19/06-3590/federal-motor-vehicle-safety-standards-low-speed-vehicles>.

[33] Korosec, K. (2018). "AutoX is using its self-driving vehicles to deliver groceries." TechCrunch. August 27, 2018. <https://techcrunch.com/2018/08/27/autox-is-using-its-self-driving-vehicles-to-deliver-groceries/>.

[34] DoorDash. (2019). "Launching the Future of Autonomous Delivery with Cruise Automation." DoorDash Blog. January 3, 2019. <https://blog.doordash.com/launching-the-future-of-autonomous-delivery-with-cruise-automation-fabf6ed7a39d>.

[35] Abuelsamid, S. (2018). "Cruising Around the Magic City with Ford and Argo AI." Forbes. November 15, 2018. <https://www.forbes.com/sites/samabuelsamid/2018/11/15/cruising-around-the-magic-city-with-ford-and-argo-ai/#1b5560175705>.

[36] Ward, T. (2019). "Walmart Begins Pilot with Autonomous Vehicle Company Gatik." Walmart Press Release. <https://corporate.walmart.com/newsroom/2019/07/25/walmart-begins-pilot-with-autonomous-vehicle-company-gatik>.

[37] Lekach, S. (2018). "In pouring rain, self-driving delivery vans show off autonomous skills." Mashable. November 29, 2018. <https://mashable.com/article/self-driving-delivery-van-hardware-thordrive/>.

Oklahoma, and Texas for multiple grocery and retail stores.[38] Waymo has been testing a grocery pickup service in Arizona using a different approach. After placing an online order with their local Walmart, customers are picked up by an automated Chrysler Pacifica and driven to the store, where they pick up their preassembled grocery orders and are then driven home.[39] More recently, Waymo has partnered with United Parcel Service (UPS) to make deliveries between UPS Store locations and a UPS sorting facility in Phoenix, AZ.[40]

Novel Design Automated Delivery Vehicles

Rather than simply modifying existing vehicle designs to enable automated delivery, some companies are designing their own novel vehicles. This category of vehicle is the most varied, as these purpose-built vehicles are designed to transport a range of different goods and include multiple business models. These vehicles are designed to operate with SAE Level 4 automation and typically do not include a driver's seat nor an on-board operator. As a result, they typically have systems for remote monitoring and operation. They may also include an HMI for customers to unlock vehicles, select items, and make payments; however, the HMI will vary based on the business model.

Some of the concepts within this category include mobile storage lockers, roving retail stores, and open platforms. Many of previous vehicle types described fit into the storage locker model (e.g., a customer must approach the vehicle and unlock it to retrieve its contents), though novel vehicle designs may allow for more storage compartments or a more flexible storage arrangement. Roving stores are like convenience stores or vending machines on wheels and carry an inventory from which customers may make selections. Customers may hail such a vehicle with a particular product in mind, or the roving store may allow for on-the-spot "impulse-buying." Some of the platforms, such as the Toyota e-Palette or the Renault EZ can be modified to accommodate a number of different uses, delivery-focused or otherwise.

Many of the companies with novel vehicle designs are not yet operating public pilots, but there are some notable examples. Some automated passenger vehicles with novel designs, such as the EasyMile EZ10 and Aurrigo PodZero, have also been used in delivery pilot testing.[41] Nuro has used its R1 vehicle to make grocery deliveries in Scottsdale, AZ, and it has partnered with other firms for activities in Houston,

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38 Etherington, D. (2019). "Udelv partners with H-E-B on Texas autonomous grocery delivery pilot." TechCrunch. July 10, 2019. <https://techcrunch.com/2019/07/10/udelv-partners-with-heb-on-autonomous-grocery-deliver-pilot/>.

39 Waymo. (2018). "Growing Waymo's Partnerships in Metro Phoenix." Medium. July 25, 2018. <https://medium.com/waymo/growing-waymos-partnerships-in-metro-phoenix-965941451902>.

40 UPS. (2020). "UPS And Waymo Partner To Begin Self-Driving Package Pickup In Arizona." UPS Press Release. January 29, 2020. <https://pressroom.ups.com/pressroom/ContentDetailsViewer.page?ConceptType=PressReleases&id=1580327674120-833>.

41 IGD. (2016). "Norway: Kolonial.no trials driverless shuttles." Institute of Grocery Distribution. October 5, 2016. <https://retailanalysis.igd.com/news/news-article/t/norway-kolonialno-trials-driverless-shuttles/i/11774>; and Aurrigo. (2018). "Coventry company celebrates driverless first in Australia." RDM Group Website. January 8, 2018. <https://aurrigo.com/tag/australia/>.

TX.[42] More recently, Nuro has been testing its R2 vehicle in California.[43] In 2019, Robomart announced its partnership with Stop & Shop to operate mobile grocery stores in the Boston area, although testing on public roads has not yet begun.[44]

Combination Automated Delivery Vehicle Models

Some automated delivery concepts combine two or more vehicles. Current combination model concepts typically use a larger “mothership” vehicle that carries both packages and smaller sidewalk delivery robots, which are deployed for the final-50-feet phase of delivery. Daimler illustrated a combination model in 2016, with a concept that combined Mercedes-Benz Sprinter vans with smaller sidewalk delivery robots from Starship Technologies. Though Daimler later invested in Starship Technologies and the companies announced a pilot project in Europe, no public information is available on testing.[45]

In 2019, Continental and Ford announced similar concepts using legged delivery robots. Continental’s concept would include a modified EasyMile EZ10 shuttle (rebranded as the “Continental Urban mobility Experience – CUbE”) that serves as a mothership for packages and an ANYbotics ANYmal robot that would deliver packages from the curb to the recipient’s front door.[46] The Ford concept would use an automated Ford Transit Connect van as the mothership and an Agility Robotics Digit robot to deliver the package.[47] Neither concept has yet been pilot tested with customers.

Workhorse, a delivery vehicle manufacturer, developed a concept that would use a delivery truck as the mothership vehicle and a small UAS to make the final delivery. In February 2017, Workhorse partnered with UPS to test the concept using a truck and UAS (called the “Workhorse Horsefly”) to deliver a package to a home in Lithia, FL.[48] In May 2018, Workhorse announced a larger pilot program in Loveland, OH as part of the Federal Aviation Administration (FAA) UAS Integration Pilot Program.[49]

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[42] Rogers, K. (2019). “Domino’s Pizza teams with robotics company Nuro to test automated delivery in Houston.” CNBC. June 17, 2019. <https://www.cnbc.com/2019/06/17/dominos-pizza-teams-with-nuro-to-test-automated-delivery-in-houston.html>.

[43] Ferguson, D. (2020). “Helping the Heroes during COVID-19.” Medium. April 22, 2020. <https://medium.com/nuro/helping-the-heroes-during-covid-19-49c189f216a2>.

[44] Bray, H. (2019). “Your city street may soon turn into a grocery aisle.” Boston Globe. January 17, 2019. <https://www.bostonglobe.com/business/2019/01/17/remote-controlled-rolling-supermarket-your-door-legal/j7fi7TE1Mo921EtuLmgbfP/story.html>.

[45] Martens, F. (2017). “Mercedes-Benz Vans invests in Starship Technologies, the world's leading manufacturer of delivery robots.” Daimler Media. January 13, 2017. <https://media.daimler.com/marsMediaSite/en/instance/ko/Mercedes-Benz-Vans-invests-in-Starship-Technologies-the-worlds-leading-manufacturer-of-delivery-robots.xhtml?oid=15274799>.

[46] Ibid. ANYbotics. (2019).

[47] Ibid. Niedermeyer. (2019).

[48] Burns, S. (2017). “Drone meets delivery truck.” UPS Website. February 22, 2017. <https://www.ups.com/us/es/services/knowledge-center/article.page?name=drone-meets-delivery-truck&kid=cd18bdc2>.

[49] Edelstein, S. (2018). “Workhorse Group’s drones are now delivering packages in Ohio.” Digital Trends. May 23, 2018. <https://www.digitaltrends.com/cars/workhorse-group-drone-delivery-pilot-program-ohio/>.

Foundational Technologies

This chapter provides background for readers who are less familiar with automated vehicles. It includes a brief introduction on some systems and components, including sensors, software, and mapping, which are foundational for automated vehicles in general, including those used for delivery service.

Sensors

Sensors allow vehicles to localize (i.e., determine where they are) and understand their surrounding environment (e.g., stationary and moving objects). The most common sensors used in automated vehicles include cameras, radar units, ultrasonic sensors, and lidar units.[50]

- **Cameras** collect image data and can be fed to algorithms for object detection and classification. Visible light cameras have limited capabilities in low-visibility conditions (e.g., inclement weather and darkness). Infrared cameras can work in darkness and have additional sensing capabilities.
- **Radar units** are commonly used in ADAS for commercially available vehicles. Radar detects and tracks objects (e.g., the speed and direction of an object). Data from radar units may not be precise enough for object classification.
- **Ultrasonic sensors** can sense only nearby objects and provide only coarse definition. In automotive applications, they are used primarily for parking assistance systems or other very low-speed maneuvering scenarios.
- **Lidar units** use lasers to create three-dimensional (3-D) images of the surrounding environment. Lidar units have distance limitations and may not be effective in some weather conditions (e.g., fog or heavy rain). The main drawbacks with lidar units include their high cost, challenges with reliability, and the tradeoff between range and resolution.

In addition to the sensors described above, automated vehicles also use other technologies, such as inertial measurement units (IMUs) and Global Navigation Satellite Systems (GNSS) for localization. IMU and GNSS technologies do not detect the surrounding environment, but are able to verify the absolute location of a vehicle.

As with other automated vehicles, automated delivery vehicles are typically equipped with a sensor suite that includes different sensor types complementing each other and serving as redundant backups in case other systems fail. Given that reducing delivery cost is one of the key goals of using automated delivery vehicles, companies generally attempt to optimize their sensor suite to balance performance considerations with cost.[51]

[50] Dawkins, T. (2019). “Autonomous Cars 101: What Sensors Are Used in Autonomous Vehicles?” Level Five Supplies Blog. January 14, 2019. <https://levelfivesupplies.com/sensors-used-in-autonomous-vehicles/>.

[51] Korosec, K. (2019). “This new autonomous startup has designed its delivery robot to conquer winter.” TechCrunch. July 11, 2019. <https://techcrunch.com/2019/07/11/this-new-autonomous-startup-has-designed-its-delivery-robot-to-conquer-winter/>.

Software

Automated vehicles fuse data from multiple sources using specialized software programs. In addition to the sensor and geolocation data described above—which monitor the operating environment—the software collects information about the vehicle itself (e.g., speed, direction, and wheel position). These data are then fused together to create a more complete "picture" of the operating environment. The software algorithms can also take into account different sensor inputs for the same object to generate more estimates that could be more precise. It can be a challenge to get different sensor systems to communicate with one another in real time and align temporally.[52] In addition, the data used to "train" automated driving algorithms often reflects basic or normal driving behavior, and may not contain less-common scenarios that involve complex, dangerous, or "near-miss" maneuvers. Such near misses and incidents need to be monitored and analyzed to be included in training and simulation so the system can successfully navigate those situations if encountered in the real world.[53]

Mapping

Approaches to mapping vary, but the concepts included in this report generally rely on high-definition (HD) maps. However, HD mapping efforts that cover broad geographic areas are resource intensive and require frequent updates to reflect changes in the built environment. HD maps are expensive to create, maintain, and transfer, since updates need to be constantly fed into and distributed by a central system. A vehicle's operating environment and sensor suite may dictate the level of mapping detail and frequency of updating. As a result, companies testing automated delivery vehicle may opt to focus on individual routes (e.g., for middle-mile business-to-business deliveries), use centralized collection and delivery points (e.g., deliver to a few select locations rather than individual addresses), or operate in a relatively small or simple network (e.g., a small neighborhood or campus rather than an entire city). A restricted test environment may help reduce costs associated with producing and updating maps.

Operating Environments

The vehicle categories and individual vehicle designs discussed in this paper have different scopes and limits to the type of operating environment in which they can safely function; in other words, they have differences in their ODDs.[54] An ODD defines the intended operational environment for a vehicle's ADS, and, therefore, when a vehicle is outside the ODD for its ADS, that system will not be able to function safely or reliably.

In some cases, an ODD may be specified by a geographical boundary (e.g., a specific stretch of roadway, a series of defined routes, or a geofenced neighborhood), but there are many other parameters that can

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[52] Tangemann, C. (2019). "Sensor Fusion: Technical challenges for Level 4-5 self-driving vehicles." Automotive IQ, International Quality and Productivity Center. October 21, 2019. <https://www.automotive-iq.com/autonomous-drive/articles/sensor-fusion-technical-challenges-for-level-4-5-self-driving-vehicles>.

[53] Koopmann, P., Kane, A., and Black, J. (2019). "Credible Autonomy Safety Argumentation." 27th Safety-critical Systems Symposium. <https://users.ece.cmu.edu/~koopman/pubs/Koopman19_SSS_CredibleSafetyArgumentation.pdf>.

[54] Since published information about automated delivery vehicle ODDs is not widely available, this section does not attempt to consider to what extent vehicles are being deployed within versus beyond their ODDs. This may be a question for future research.

be defined, such as the range of speeds, road types, or weather conditions in which an automated system can operate. Formally, ODD is defined by SAE Standard J3016 as the "operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics."[55] SAE International has developed best practices for describing ODDs,[56] and others have identified factors that should be included when characterizing ODDs.[57]

In many cases, the same ODD factors that apply to automated vehicles broadly also apply to automated delivery vehicles, though in some cases automated delivery vehicles may have unique considerations. Beyond operating on roadways, automated delivery vehicles may need to operate in logistics yards or indoor environments (e.g., in a warehouse or other facility) and may need to interface with loading docks.

There are also unique factors for sidewalk delivery robots, which operate in an environment of walkways, building interiors, and other pedestrian areas, with a wide range of users, behaviors, and norms. These delivery robots face a different set of operational terrains, infrastructure, and rules of engagement compared to other automated vehicles, and may have relatively complex operating environments. Some researchers have questioned the compatibility of motorized vehicles with pedestrian traffic and their suitability on sidewalks.[58]

[55] Ibid. SAE. (2018).

[56] SAE. (2020). "AVSC Best Practice for Describing an Operational Design Domain: Conceptual Framework and Lexicon." SAE International. April 15, 2020. <https://www.sae.org/standards/content/avsc00002202004/>.

[57] Koopmann, P. (2019). "How Many Operational Design Domains, Objects, and Events?" Safe AI 2019: AAAI Workshop on Artificial Intelligence Safety, January 27, 2019. <https://users.ece.cmu.edu/~koopman/pubs/Koopman19_SAFE_AI_ODD_OEDR.pdf>.

[58] Wong, J.C. (2017). "Delivery robots: a revolutionary step or sidewalk-clogging nightmare?" The Guardian. April 12, 2017. <https://www.theguardian.com/technology/2017/apr/12/delivery-robots-doordash-yelp-sidewalk-problems>.

Chapter 3. Industry Structure and Activity

A review of industry activity related to automated delivery vehicles revealed participation from a range of different companies engaging in various activities. This chapter discusses various roles of industry participants and characterizes automated delivery vehicle testing activities, both internationally and domestically.

Industry Structure

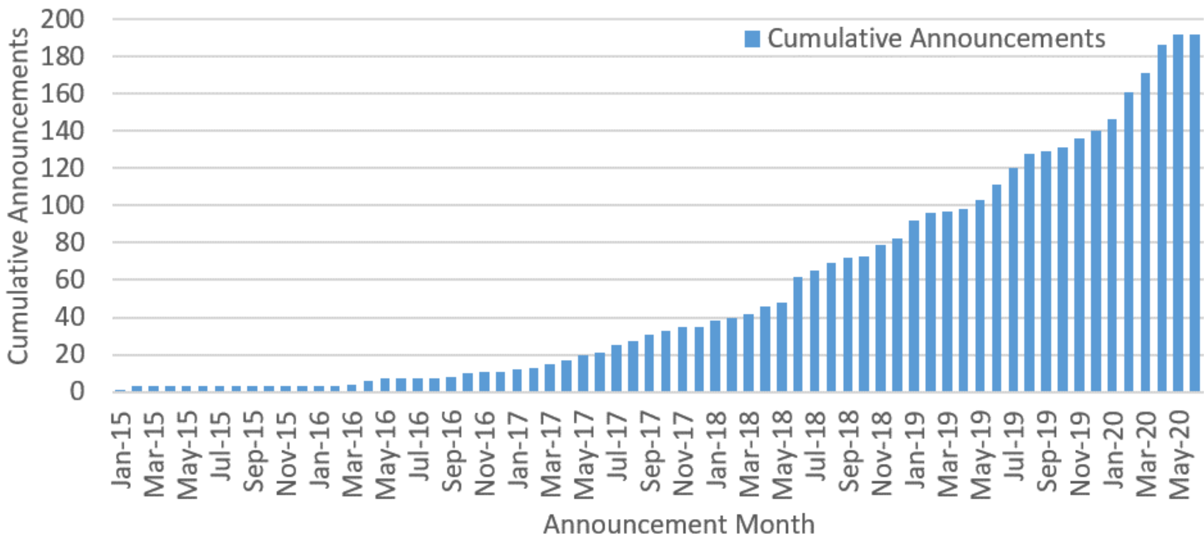
Companies active in the automated delivery vehicle space fill a variety of different roles—while some develop new vehicles or supporting systems, others develop new service models or provide fleet management services. Some of these roles include:

- **Hardware and software developers**, which produce the ADS hardware and software, such as sensors, controls, and algorithms. Such companies may produce individual components or entire systems.
- **Specialized operations and maintenance support companies**, which provide ADS maintenance, operations, or data such as high-definition maps. Such companies may provide technical and operational support, specialize in maintaining vehicles and systems, provide teleoperation and security monitoring, or other support.
- **Platform integrators**, which customize and create automated delivery platforms that they offer to retail and logistics customers. Such companies combine various inputs from hardware and software developers to create an automated delivery vehicle.
- **Service model integrators**, which offer delivery services using automated delivery vehicles, much as companies such as Uber, Postmates, and DoorDash have become service model integrators for human-based service models. Such companies may work to translate existing service models to incorporate automated vehicles, or they may develop new service models.
- **Retail and logistics customers**, which use automated delivery vehicles to support their core business. Such companies typically contract with one or multiple companies to fulfill the previously described roles, but in some cases they may have their own internal efforts to develop and test automated delivery vehicle technologies.

These roles are not mutually exclusive, and a single firm may take on multiple roles as part of its automated delivery vehicle activities. There may even be some companies with a "vertically integrated" approach that addresses all the roles described above.

Industry Activity

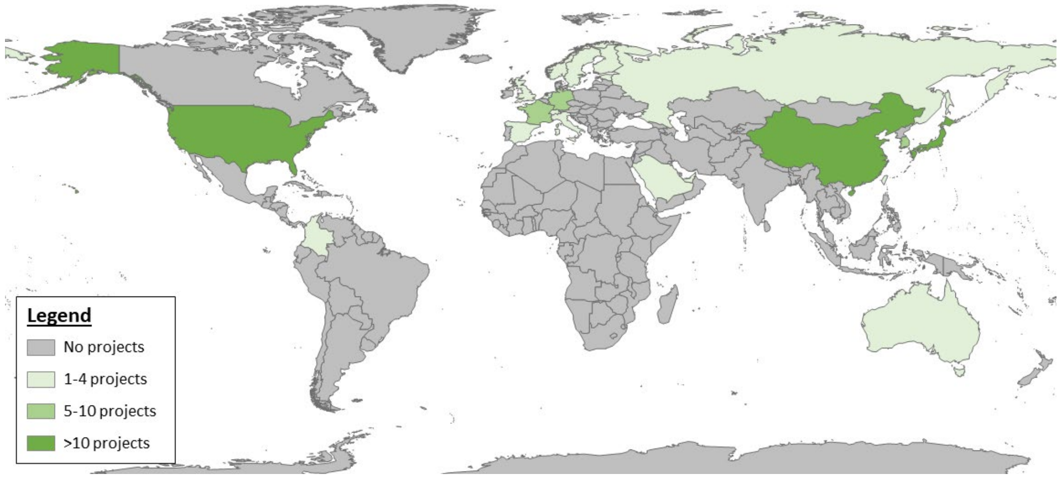
Automated delivery vehicle activities are a relatively recent development and most companies engaged in such activities are testing prototype vehicles. Although the first few identified activities were announced in 2015, nearly 60 percent of the activities identified by the project team were announced since the beginning of 2019. As of mid-June 2020, nearly 200 concepts, demonstrations, and pilot testing activities were identified that featured automated delivery vehicles, including projects that were completed, ongoing, or planned. Figure 2 displays a cumulative count of automated delivery vehicle activities arranged by announcement date (either when an official press release was issued or when a project first received media coverage).



Source: USDOT Volpe Center 2020

Figure 2. Chart of Cumulative Automated Delivery Vehicle Announcements (2015-2020)

Nearly 200 automated delivery vehicle activities were found across the world, with projects in North America, Asia, Europe, Asia, Oceania, and South America. Approximately half of those activities were in the United States (51 percent), with the majority of other projects occurring in Asia (29 percent) or Europe (18 percent), though it is important to note that the information gathered as part of the tracking effort has a bias toward the inclusion of projects in the United States and projects that have received English-language media attention. Figure 3 illustrates where worldwide automated delivery vehicle activities are located.



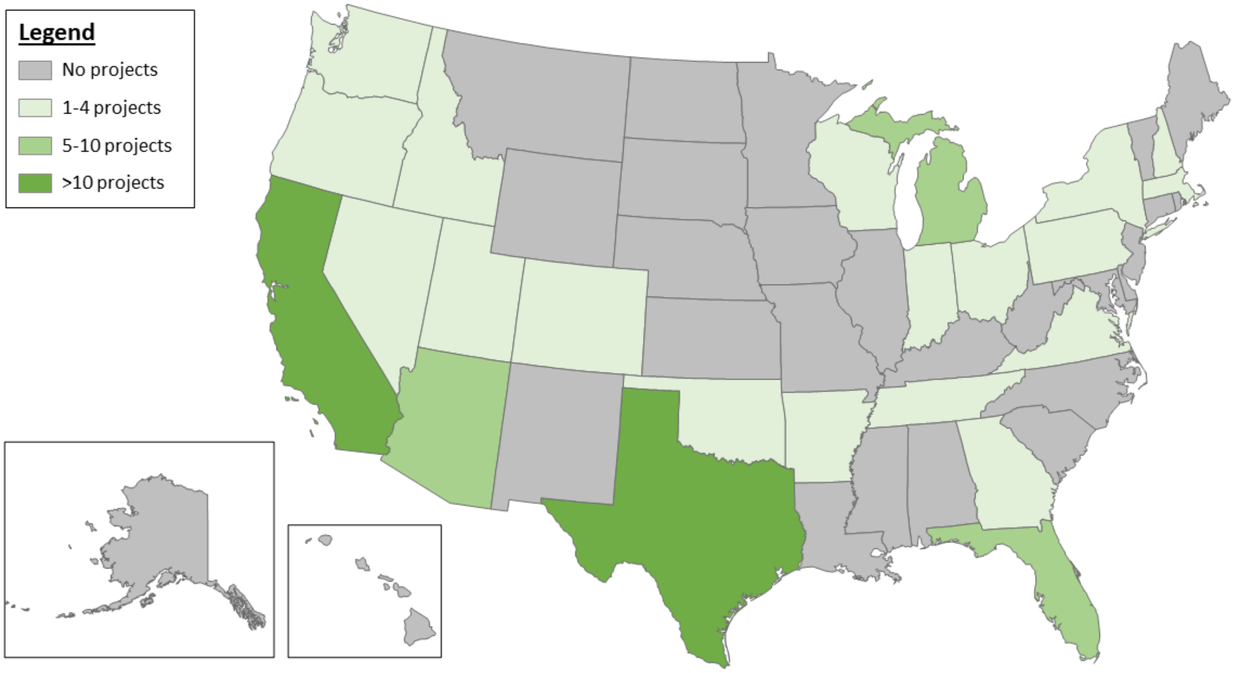
Source: USDOT Volpe Center 2020

Figure 3. Map of Identified International Automated Delivery Vehicle Activity by Country

Companies choose test locations for automated delivery vehicle activities based on considerations such as proximity to their own facilities (e.g., headquarters or R&D centers), partner facilities, or industrial centers (e.g., where skilled labor, capital, and supporting industries may be more readily available). Other factors include environment complexity (e.g., weather, road, and traffic conditions) and the local regulatory environment (e.g., whether testing is allowed, as well as permitting, operating, and reporting requirements). In some cases, government initiatives (e.g., grant programs) will influence test locations.

International regions for automated delivery vehicle test activity in Asia include Beijing and Shenzhen in China, Tokyo in Japan, and Seoul in South Korea. In Europe, activity is spread across multiple countries, though France and Germany, which host many of the headquarters and R&D facilities for European automakers and their suppliers, have slightly more activity than other nations. Within France, the majority of activity centers around Paris.

Within the United States, there are at least 23 States (and Washington, DC) that have hosted some level of activity (or will do so in the near future) related to automated delivery vehicles. Figure 4 illustrates the distribution of domestic automated delivery vehicle activities.



Source: USDOT Volpe Center 2020

Figure 4. Map of Identified Domestic Automated Delivery Vehicle Activity by State

California is the most active State, with more than a third of all domestic automated delivery vehicle activities occurring there. California's activities are largely concentrated in the San Francisco Bay area, where many technology firms, including several automated vehicle companies have located their headquarters or R&D facilities. The San Francisco Bay area's history of electronics, semiconductor, and software development has led to a concentration of technology companies, talent, and investment capital that support a start-up ecosystem. As such, the region is host to many technology startups (e.g., Cruise, Kiwi, Marble, Nuro, Postmates, Robby, and Waymo) that have developed platforms to address delivery use cases.

Michigan is also host to several companies testing automated delivery vehicles. In addition, the automotive ecosystem of southeast Michigan has resulted in automated vehicle start-up activity, including some automated delivery vehicle firms (e.g., Bedestrian and Refraction AI). Texas, Arizona, and Florida are often cited as States with relatively mild weather and regulatory environments that support automated vehicle testing, and those States have attracted companies interested in testing automated delivery vehicles.

While much of the automated delivery vehicle test activity, both domestically and abroad, has been steadily progressing over the past few years, the recent coronavirus (COVID-19) public health emergency served as a catalyst to accelerate automated delivery vehicle testing, as companies have sought ways to simultaneously address increased demand for delivery while reducing person-to-person contact. During the first few months of the public health emergency in the United States, many companies testing automated delivery vehicles (e.g., Kiwi, Nuro, Refraction, and Starship) continued or even expanded their operations to deliver to customers, and often adapted their operations to address the needs of those using their services. In addition, some companies that had been testing automated vehicles for passenger service (e.g., Cruise, Hyundai-Aptiv, Navya, and Pony.ai) repurposed their vehicles to make deliveries.

While many companies have been active in automated delivery vehicle activities during the public health emergency, service has been relatively limited in terms of its geographic scale and number of vehicles actively making deliveries. Some observers noted automated vehicles could have played a larger role in making deliveries during the public health emergency, but were constrained by the technology's capabilities and limited capacity to rapidly manufacture more automated delivery vehicles.[59] For more discussion of automated delivery vehicle activities related to the COVID-19 public health emergency, see Appendix E.

Remote Monitoring and Teleoperation

As with other types of automated vehicles, remote monitoring and teleoperation may be used to support operation of automated delivery vehicles.[60] In discussions, industry stakeholders identified a range of approaches to remote monitoring and teleoperation. Remote monitoring and teleoperation are integral to some concepts, while others use on-board operators or a combination of on-board operators and remote monitoring in their testing. Some companies use chaperones with a line of sight to the vehicle (following on foot or in a chase vehicle), though they may later transition to remote support. Not all automated delivery vehicles can accommodate an on-board operator (e.g., sidewalk delivery robots and other vehicles with novel designs). For some companies or concepts, the intended business case may eventually require a teleoperator to manage multiple vehicles. While most companies are currently using a teleoperator for each vehicle, some have conducted testing with a teleoperator simultaneously managing two or three vehicles.[61]

Consumer Acceptance and Public Sentiment

Consumer acceptance and public sentiment are seen as critical factors that may help determine whether automated delivery vehicles will be broadly adopted. Consequently, pilot testing activities seek to answer questions beyond simply evaluating the technical capabilities and performance of a given automated delivery system. Some companies conducting such testing have claimed that understanding the experiences and opinions of customers who receive deliveries and interact with vehicles can help them improve their vehicles and service models. Similarly, firms state they may also seek input from the general public to gauge how other people in a service area perceive automated delivery vehicles.

There is limited research on consumer acceptance of and specific reactions to automated delivery vehicles, outside of work associated with individual pilot projects. Some research firms, think tanks, and

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[59] Templeton, B. (2020). "Delivery Robots Could Have Saved The Day If The Virus Had Come A Bit Later." Forbes. March 19, 2020. <https://www.forbes.com/sites/bradtempleton/2020/03/19/delivery-robots-could-have-saved-the-day-if-the-virus-had-come-a-bit-later/#260fcfeb76c5>; and Beans, C. (2020). "This Would Be a Really Great Moment for Food Delivery Robots." Slate. March 25, 2020. <https://slate.com/technology/2020/03/where-are-food-delivery-robots.html>.

[60] Bishop, R. (2020). "Remote Support to Accelerate ADS Deployment." Plenary Session at Automated Vehicle Symposium 2020. July 30, 2020. <https://automatedvehiclessymposium.org/home>.

[61] See for example: Sawers, P. (2020). "Einride demos a single teleoperator taking control of multiple autonomous trucks." VentureBeat. April 7, 2020. <https://venturebeat.com/2020/04/07/einride-demos-a-single-teleoperator-taking-control-of-multiple-autonomous-trucks/>; and Korosec, K. (2020). "Kiwibot Delivery Robots Head to San Jose with New Partners Shopify and Ordermark." TechCrunch. July 21, 2020. <https://techcrunch.com/2020/07/21/kiwibot-delivery-robots-head-to-san-jose-with-new-partners-shopify-and-ordermark/>.

academic institutions have conducted broad surveys over the past few years to understand the public's interest and sentiment as it relates to automated vehicles. According to a review of survey results reported from academic sources and through news outlets, most surveys focus on attitudes toward automated vehicles (e.g., interest in riding in or owning an automated vehicle and perceptions related to safety and trust) for the general population or for a specific group of Americans.[62] However, these studies can be of limited scope and utility due to their hypothetical nature and the lack of public experience with actual operational technologies.

A few surveys have been conducted repeatedly in the past few years to capture the potential change of public sentiment toward automated vehicles over time. A multi-year survey from Deloitte from 2017 to 2019 found that approximately 50 percent of American consumers are concerned that automated vehicles will not be safe.[63] Due to the novelty of the technology, most respondents did not have real-world experience of riding in an automated vehicle, which may prevent policymakers from drawing any meaningful conclusions regarding the readiness of the public to automated technologies. Other surveys implied that Americans still show resistance to automated vehicles in general.[64]

There are relatively few surveys regarding consumers' attitudes toward automated delivery vehicles. An American Automobile Association (AAA) survey in 2019 showed that 44 percent of respondents would be comfortable with automated vehicles delivering food or packages. Notably, those same respondents were less open to automated vehicles for passenger transportation: 71 percent noted that they would be afraid to ride in an automated vehicle themselves, and only 19 percent noted that they would be comfortable with the use of automated vehicles to transport their children or loved ones.[65]

In 2018, the U.S. Postal Service Office of Inspector General conducted an online survey to gauge public sentiment for "helper" and "independent" mail delivery robots. In general, findings were positive regarding the use of delivery robots—and "helper" robots working with a human to deliver mail were preferred compared to "independent" delivery robots.[66]

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[62] Hassol, J., Perlman, D., Chajka-Cadin, L., and Shaw, J. (2019). "Understanding Surveys of Public Sentiment Regarding Automated Vehicles: Summary of Results to Date and Implications of Past Research on the Dynamics of Consumer Adoption." ITS Joint Program Office, U.S. Department of Transportation. November 1, 2019. <https://trid.trb.org/view/1688128>.

[63] Deloitte. (2019). "2019 Deloitte Global Automotive Consumer Study: Advanced Vehicle Technologies and Multimodal Transportation." Deloitte. January 2019. <https://www2.deloitte.com/content/dam/Deloitte/us/Documents/manufacturing/us-global-automotive-consumer-study-2019.pdf>; and Deloitte. (2020). "2020 Global Automotive Consumer Study: Is Consumer Interest in Advanced Automotive Technologies on the Move?" Deloitte. January 2020. <https://www2.deloitte.com/us/en/pages/manufacturing/articles/automotive-trends-millennials-consumer-study.html>.

[64] Ibid. Hassol, et al. (2019).

[65] AAA. (2019). "Three in Four Americans Remain Afraid of Fully Self-driving Vehicles." American Automobile Association. March 14, 2019. <https://newsroom.aaa.com/2019/03/americans-fear-self-driving-cars-survey/>.

[66] USPS. (2018). "Summary report: Public perception of delivery robots in the United States." Report Number RARC - WP- 005. Office of Inspector General, United States Postal Service. April 9, 2018. <https://www.uspsoig.gov/document/public-perception-delivery-robots-united-states>.

In June 2020, the Consumer Technology Association released the results of a survey focused specifically on understanding the public awareness of and sentiment toward automated delivery vehicles.[67] Of 1,004 survey respondents, 22 percent indicated that they were either “very” or “somewhat familiar” with sidewalk delivery robots and 31 percent were either “very” or “somewhat familiar” with larger automated delivery vehicles. Around half of respondents indicated they are “very” or “somewhat favorable” toward the technologies surveyed (50 percent for sidewalk delivery robots and 48 percent for larger automated delivery vehicles). Regionally, respondents in the Northeast and West indicated higher favorability than respondents in the Midwest and South. Respondents from urban areas indicated higher favorability ratings than those in suburban and rural areas. Younger age groups indicated higher favorability ratings than older age groups. Roughly a quarter of respondents indicated sidewalk delivery robots and larger automated delivery vehicles more favorably than before the COVID-19 public health emergency.

Surveys are not the only way to obtain information on public sentiment. Researchers have adopted other methods, such as content analysis of news articles and social media, to gauge public sentiment. Some recent studies analyzed social media content to understand public perceptions of automated delivery vehicles.[68] Key concerns conveyed by individuals include safety, security/privacy, employment impacts, traffic/congestion, and environmental impacts. Results from such studies may vary by culture, location, and familiarity (e.g., the extent of local automated delivery vehicle activity). While social media data offers opportunities to address questions about public attitudes and social behavior, it is important to consider data representativeness and sampling biases, given that individuals self-select whether to post information on social media and the privacy settings of those posts, so utilizing social media posts may not represent the attitudes of any group as a whole.[69]

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[67] CTA. (2020). “Autonomous Delivery Systems: Consumer Awareness & Favorability.” Consumer Technology Association. June 2020. <https://shop.cta.tech/collections/research/products/autonomous-delivery-systems-consumer-awareness-and-favorability>.

[68] Io, H.N., and Lee, C.B. (2019). “What are the sentiments about the autonomous delivery robots?” Proceedings of the 2019 IEEE IEEM. December 15-18, 2019. <https://ieeexplore.ieee.org/document/897892>; and Buch, R., Beheshti-Kashi, S., Nielsen, T.A.S., and Kinra, A. (2018). “Big Data Analytics: a case study of public opinion towards the adoption of driverless car.” In: Freitag M., Kotzab H., Pannek J. (eds) Dynamics in Logistics. LDIC 2018. Lecture Notes in Logistics. Springer, Cham. January 2018. <https://www.researchgate.net/publication/323222441_Big_Data_Analytics_A_Case_Study_of_Public_Opinion_Towards_the_Adoption_of_Driverless_Cars>.

[69] Hargittai, E. (2018). “Potential Biases in Big Data: Omitted Voices on Social Media.” Social Science Computer Review, (38)1 July 30, 2018. <http://www.mkoganresearch.com/assets/hargittai.pdf>.

Chapter 4. Policy and Regulation

Automated delivery vehicles represent new ways in which technologies interact within the public space and thus raise novel questions related to policy and regulation at multiple levels of government. This chapter summarizes the relevant regulatory context and the current approaches being pursued by State and local governments.[70]

Context

In the last decade, policymakers have been grappling with the introduction of new technologies onto public roads (e.g., TNCs), sidewalks (e.g., micromobility services, such as e-scooters), and the national airspace (e.g., UAS). While these precedents suggest some considerations that may be relevant for automated delivery vehicles, there are enough unique features in the delivery vehicle environment that make it difficult to draw clear parallels. The regulation of the national airspace is controlled by a central authority (i.e., FAA). Motor vehicle and motor vehicle equipment safety is regulated by NHTSA and operation of motor vehicles by States, with some local and tribal government participation. Operation of commercial motor vehicles in interstate commerce is regulated by FMCSA. Sidewalks, however, have traditionally been regulated at the local level, with standards for width, design, and usage varying by community, neighborhood, or even block, as is the case in some historic districts.[71]

The rapid introduction of TNCs created an international conversation around disruptive technology, and forced State and local governments to reassess their longstanding regulation of taxi and livery industries and develop new policy positions around TNCs.[72] While a full discussion is outside the scope of this paper, it is worth noting that the high profile of this issue set the stage for local government responses to the introduction of micromobility services, as discussed below.

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[70] For further reading on this topic, see Jennings, D., and Figliozzi, M.A. (2019). "A Study of Sidewalk Autonomous Delivery Robots and Their Potential Impacts on Freight Efficiency and Travel." Transportation Research Record. 2019, Vol. 2673(6) 317–326.; and Thomasen, Kristen. (2020) "Out of their Cages and into the City: Robots, Regulation, and the Changing Nature of Public Spaces." Ottawa Law Review Working Paper Series. 2020, No. 2.

[71] For example, see NYC. (2012). "Site Work Application Guidelines: Sidewalks, Sidewalk Cafes, Yards and Areaways." NYC Landmarks Preservation Committee. <https://www1.nyc.gov/assets/lpc/downloads/pdf/pubs/App_Guide_Site_Work.pdf>.

[72] SFCTA. (2017). "The TNC Regulatory Landscape: An Overview of Current TNC Regulation in California and Across the Country." San Francisco County Transportation Authority. December 2017. <https://www.sfcta.org/sites/default/files/2019-03/TNC_regulatory_020218.pdf>; Moran, M., Ettelman, B., Stoeltje, G., Hansen, T., and Pant, A. (2017). "Policy Implications of Transportation Network Companies." Texas A&M Transportation Institute. October 2017. <https://static.tti.tamu.edu/tti.tamu.edu/documents/PRC-17-70-F.pdf>.

Regulatory Environment

Automated delivery vehicles are a diverse group, as discussed in the chapter on Automated Delivery Vehicle Taxonomy, and the relevance of Federal, State, and local regulations vary accordingly. This chapter briefly summarizes the regulatory environment for automated delivery vehicles; the reader should note that this is an emerging area and subject to change.

Roadways (Public or Private)

Automated delivery vehicles manufactured primarily for use on public streets, roads, and highways are governed by the same Federal, State, and local laws and regulations that apply to conventional motor vehicles. At the Federal level, NHTSA regulates the performance of motor vehicles and motor vehicle equipment through FMVSS and other regulations. NHTSA's general approach to ADS is discussed in its guidance, *A Vision for Safety: Automated Driving Systems 2.0* and USDOT's guidance, *Automated Vehicles 3.0: Preparing for the Future of Transportation*.[73] All motor vehicles and motor vehicle equipment must meet applicable FMVSS or have an approved exemption.

Manufacturers of vehicles that do not comply with the FMVSS must request an exemption from NHTSA, except under very limited circumstances.[74] To date, Nuro is the only manufacturer of a vehicle equipped with an ADS to have received an exemption from certain requirements of FMVSS Part 500, such as mirrors and a windshield for its R2 vehicle.[75] The exemption is for a period of two years, includes a maximum number of vehicles (5,000) to be produced and deployed, and carries additional reporting requirements. NHTSA also has a process for entities to receive temporary exemptions for the importation of non-compliant vehicles for research and demonstration purposes.[76] If the importer does not manufacture vehicles that comply with all applicable FMVSS, they must apply for permission from NHTSA. Some of the vehicles imported under this process, such as those from EasyMile and Navya, have been used in testing automated delivery vehicle concepts.

In addition, some State and local governments have passed legislation specific to ADS testing and operation.[77] California, home to a relatively high number of ADS developers and automated delivery

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[73] USDOT. (2017). "Automated Driving Systems 2.0: A Vision for Safety." U.S. Department of Transportation. September 12, 2017. <https://www.nhtsa.gov/sites/nhtsa.dot.gov/files/documents/13069a-ads2.0_090617_v9a_tag.pdf>; and USDOT. (2018). "Preparing for the Future of Transportation: Automated Vehicles 3.0." U.S. Department of Transportation. October 4, 2018. <https://www.transportation.gov/sites/dot.gov/files/docs/policy-initiatives/automated-vehicles/320711/preparing-future-transportation-automated-vehicle-30.pdf>.

[74] 49 U.S.C. 30112(b)(10) permits certain manufacturers to operate noncompliant vehicles on public roads for testing and evaluation purposes.

[75] NHTSA. (2020). "NHTSA Grants Nuro Exemption Petition for Low-Speed Driverless Vehicle" National Highway Traffic Safety Administration, U.S. Department of Transportation. February 6, 2020. <https://www.nhtsa.gov/press-releases/nuro-exemption-low-speed-driverless-vehicle>.

[76] NHTSA. (2020). "Information for Importing a Vehicle." National Highway Traffic Safety Administration, U.S. Department of Transportation. Accessed June 2020. <https://www.nhtsa.gov/importing-vehicle>.

[77] For updated information on the status of state legislation related to automated vehicles, see NCSL. (2020). "Autonomous Vehicles State Bill Tracking Database." National Conference of State Legislatures.

companies, initially excluded commercial vehicle operations, but recently amended its regulations to authorize light-duty autonomous delivery vehicles weighing less than 10,001 pounds.[78] This action paved the way for Nuro to receive a permit for testing a vehicle without a human driver in designated locations in California.[79] As noted in Chapter 3, testing and pilot operation of on-road automated delivery vehicles is also underway in Arizona, Alabama, and Texas.

Sidewalk and Pedestrian Paths

Regulation of public pedestrian spaces is typically controlled at the local government level and accordingly there is significant variation in the presence or absence of dedicated pedestrian facilities such as sidewalks or paths and the design and use standards that apply to them. Nationally, accessibility standards apply to public sidewalks where provided, although local governments may choose to exceed these.[80] Organizations such as the Institute of Transportation Engineers and the National Association of City Transportation Officials publish voluntary standards and guidelines for best practices regarding sidewalk design.[81]

Sidewalks have historically been intended primarily for use by pedestrians, defined broadly to include pedestrians using mobility devices (e.g., wheelchairs or powered chairs). However, the introduction of unattended automated delivery vehicles onto these spaces has no real precedent. Wide variations already exist among cities (and often between different areas within the same city) and across States. For example, some locales permit bicycles on sidewalks, while others prohibit them. Similarly, some locales permit businesses to encroach on the public sidewalk with dining tables and signage. Local government responses to the introduction of e-scooters, which have often been parked—or abandoned—in pedestrian spaces, may be instructive examples. The rapid growth of these services in certain cities has led to concerns from local officials, residents, and disability advocates regarding safety and accessibility.[82] In

March 20, 2020. <https://www.ncsl.org/research/transportation/autonomous-vehicles-legislative-database.aspx>.

[78] California DMV. (2019). “California Authorizes Light-Duty Autonomous Delivery Vehicles.” California Department of Motor Vehicles. December 17, 2019. <https://www.dmv.ca.gov/portal/news-and-media/california-authorizes-light-duty-autonomous-delivery-vehicles/>.

[79] California DMV. (2020). “DMV Authorizes Nuro to Test Driverless Delivery Vehicles in Portion Of Bay Area.” California Department of Motor Vehicles. April 7, 2020. <https://www.dmv.ca.gov/portal/dmv/detail/pubs/newsrel/2020/2020_16>.

[80] Access Board. (2001). “X02 New Construction: Minimum Requirements: X02.1 Public Sidewalks.” Public Rights-of-Way Access Advisory Committee Final Report. United States Access Board. January 2001. <https://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/background/access-advisory-committee-final-report/x02-new-construction-minimum-requirements-x02-1-public-sidewalks>.

[81] NACTO. (2013) “Urban Street Design Guide.” National Association of City Transportation Officials. October 2013. <https://nacto.org/publication/urban-street-design-guide/street-design-elements/sidewalks/>; and CNU. (2017). “CNU/ITE Manual.” Congress for the New Urbanism. <https://www.cnu.org/our-projects/cnu-ite-manual>.

[82] Marshall, A. (2018). “Discombobulated Cities Wrestle With an Electric Scooter Influx.” Wired. April 17, 2018. <https://www.wired.com/story/discombobulated-cities-electric-scooters/>.

many areas, local governments have established permit programs or other caps on the number and use of e-scooters.[83]

Automated delivery vehicles that primarily operate in pedestrian spaces are generally not within the scope of driving automation-specific legislation passed by State and local governments. Relatively few localities have addressed these vehicles, which may reflect the very early stage of testing and commercialization activity. Some local governments (e.g., Washington, DC and West Hollywood, CA) established pilot programs as a first step toward setting operational policies.[84] Several states and some cities have begun to pass relevant bills and ordinances setting parameters on the operation of sidewalk-based automated delivery vehicles, as summarized in Table 2.[85] State laws vary with respect to how they treat preemption over local control. Media sources have suggested that advocacy from the automated delivery industry contributed to the passage of these ordinances.[86] In States where local control is not preempted, cities may also choose to prohibit use of automated delivery vehicles. For example, Nashville, TN banned "personal delivery devices" from operating on public rights of way due to concerns over accessibility issues,[87] and Madison, WI banned them from operating on public sidewalks unless approved by the City Traffic Engineer.[88]

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[83] For example, Providence, Rhode Island (https://www.providenceri.gov/planning/e-scooter-share-pilot-program/) and Orlando, Florida (https://www.orlando.gov/Initiatives/Bike-Share-Scooter-Share-Pilot-Program)

[84] While early testing may provide some useful information to host communities, small-scale pilot activities that use relatively few vehicles may not reveal some issues that may only become apparent through larger-scale pilot testing.

[85] Note that this review is not comprehensive. It did not touch on standards and regulations that focus on authorities outside of the Department of Transportation—for example, those set by the Consumer Product Safety Commission—as these are outside of the research team's expertise.

[86] Glaser, A. (2017). "A robot-delivery startup helped write state laws that are locking out competition." Vox. April 22, 2017. <https://www.vox.com/2017/4/22/15273698/robot-delivery-startup-starship-state-laws-lock-out-competitors>; and Capriel, J. (2020). "Amazon's self-driving delivery robots are green-lit for Virginia. And not just on sidewalks." Washington Business Journal. February 20, 2020. <https://www.bizjournals.com/washington/news/2020/02/25/amazons-self-driving-delivery-robots-are-virginia.html>.

[87] See Bill BL2020-333 at https://www.nashville.gov/Metro-Clerk/Legislative/Ordinances/Details/c193a4be-0497-4199-b482-6b4039e01a12/2019-2023/BL2020-333.aspx.

[88] Note that Madison exempted the University of Wisconsin's campus from the ban. At the time that the ordinance was passed, the University was hosting a pilot of food delivery with Starship. Gretzinger, E. (2020). "City passes ordinance prohibiting delivery robots operation, UW Starship robots exception" The Badger Herald. February 4, 2020. <https://badgerherald.com/news/2020/02/04/city-passes-ordinance-prohibiting-delivery-robots-operation-uw-starship-robots-exception/>.

Table 2. Sample State and Local Regulations for Automated Delivery Vehicles

Law / Legislation	Location	Terminology	Maximum Weight	Maximum Speed	Maximum Vehicles	Minimum Liability
HB 2365 (2020)	State of Tennessee	Personal Delivery Device	N/A	10 mph	N/A	$100,000
SB 758 (2020)	State of Virginia	Personal Delivery Device	500 lbs., excluding cargo	10 mph	N/A	$100,000
HB 1325 (2019)	State of Washington	Personal Delivery Device	120 lbs., excluding cargo	6 mph	N/A	$100,000
HB 2422 (2018)	State of Arizona	Personal Delivery Device	<200 lbs.	7 mph	N/A	$100,000
HB 217 (2018)	State of Utah	Personal Delivery Device	<150 lbs., excluding cargo	10 mph	N/A	$100,000
4511.513 (2017)	State of Ohio	Personal Delivery Device	<90 lbs., excluding cargo	10 mph	N/A	$100,000
HB 204 (2017)	State of Idaho	Personal Delivery Device	<80 lbs., excluding cargo	10 mph	N/A	N/A
HB 1027 (2017)	State of Florida	Personal Delivery Device	<80 lbs., excluding cargo	10 mph	N/A	$100,000
SB 148 (2017)	State of Wisconsin	Personal Delivery Device	<80 lbs., excluding cargo	10 mph	N/A	N/A
Ordinance No. 244-17 (2017)	City of San Francisco, CA	Autonomous Delivery Device	100 lbs. per square foot for wheel loads	3 mph	3 per permit; 9 permits total	$1,000,000
21-160 (2016) **22-137** (2018)	City of Washington, DC	Personal Delivery Device	<90 lbs., excluding cargo	10 mph	5	N/A

Source: USDOT Volpe Center 2020

Chapter 5. Network Impacts

Road infrastructure plays an important role in enabling automated delivery vehicle services. However, due to the nascent nature of the technology, relatively little attention has been given toward issues related to the relationship between road infrastructure (e.g., roads, curbs, and sidewalks) and automated delivery vehicles. This chapter highlights three types of public space—road space, curb space, and sidewalk space—that could influence the implementation of automated delivery services and the potential impact of automated delivery vehicles on road system performance.

Sidewalk Space

The two types of sidewalk delivery robots—wheeled and legged—operate mainly on sidewalks. The primary requirement for sidewalk delivery robots is a suitable network of sidewalks that are wide enough to allow robots to move safely among pedestrians. Adding automated delivery robots to places where sidewalks are relatively narrow (e.g., dense urban areas) or have high pedestrian traffic volume (e.g., areas near schools, parks, and shopping districts) could lead to congested sidewalks. Therefore, some local governments may limit the operation of sidewalk delivery robots in certain zones.[89] Vulnerable road users (e.g., older adults and people with disabilities) have expressed concerns about potential sidewalk obstruction or safety hazards and there have been instances where people have experienced difficulties navigating the sidewalks where those robots operate.[90]

While various organizations provide sidewalk design guidance, in practice, sidewalk design and maintenance are not uniform from city to city or even within a city.[91] The Americans with Disabilities Act (ADA) requires a minimum width of three feet for sidewalks (with wider passing areas at regular

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89 Penn, B., Lewis, J., and Anderson-Hall, K. (2019). “Urban Technology Studies: Delivery Robots.” Chaddick Institute, DePaul University. March 2019. <https://las.depaul.edu/centers-and-institutes/chaddick-institute-for-metropolitan-development/research-and-publications/Documents/Urban%20Technology%20Studies%20-%20Delivery%20Robots.pdf>.

90 Lenthang, M. (2019) “Food delivery robots that travel on the sidewalk branded a menace for disabled people.” Daily Mail. November 21, 2019. <https://www.msn.com/en-us/news/technology/autonomous-food-delivery-robots-that-are-just-knee-high-and-travel-on-the-sidewalk-on-college-campuses-are-branded-a-menace-for-disabled-people/ar-BBX3MXn>.

91 FHWA. (2020). “Lesson 13 - Walkways, Sidewalks, and Public Spaces.” FHWA Course on Bicycle and Pedestrian Transportation. Accessed June 10, 2020. <https://safety.fhwa.dot.gov/ped_bike/univcourse/pdf/swless13.pdf>; Hilberry, G., Hilton, E., Prosser, W., and Franck, L. (2007). “Accessible Public Rights-of-Way Planning and Design for Alterations: Chapter 5—Model Sidewalks.” Public Rights-of-Way Access Advisory Committee (PROWAAC), Subcommittee on Technical Assistance, The Access Board. August 2007. <https://www.access-board.gov/guidelines-and-standards/streets-sidewalks/public-rights-of-way/guidance-and-research/accessible-public-rights-of-way-planning-and-design-for-alterations/chapter-5%E2%80%94model-sidewalks>; FHWA. (2003). “Accessible Sidewalks and Street Crossings—an informational guide.” Federal Highway Administration, USDOT. January 1, 2003. <https://nacto.org/docs/usdg/accessible_sidewalks_and_street_crossings_boodlal.pdf>.

intervals).[92] Other guidance documents identify four feet as the minimum width for sidewalks, with preference for five-foot widths. In addition, six-foot-wide sidewalks are required to enable two wheelchair users to pass each other.[93] Sidewalks that meet only minimum width requirements may not be wide enough to enable sidewalk delivery robots to pass other sidewalk users. Sidewalk design guidance also includes keeping the pathways as level as possible, but poor maintenance can lead to problems such as broken or uneven surfaces, sunken areas that collect water, vegetation overgrowth, and obstacles, all of which may make it difficult for sidewalk delivery robots—and human users—to navigate.

Issues such as sidewalk maintenance and snow removal may be a challenge for deployment of some automated delivery vehicle concepts. Maintenance backlogs are common, and in many communities, the abutting property owner bears some responsibility for upkeep, which may complicate any effort to maintain a particular standard. Materials vary greatly within communities (e.g., brick, concrete, asphalt, pavers). Information on sidewalk conditions is not available nationally, but deferred or substandard maintenance of sidewalk networks has led to reduced walkability of numerous neighborhoods.[94] Many cities and States have asset management plans that capture some of this information, and although some boast near-ideal conditions, many paint a bleak picture of an ailing infrastructure.[95] For example, the City of Austin, TX cites achieving 55 percent functionality for their sidewalk network as a 10-year goal,[96] and the City of Portland, OR reports 35 percent of their sidewalks are in “poor” or “very poor” condition.[97] Deficient sidewalk conditions or lack of sidewalks in some areas may preclude the operation of some automated delivery vehicles to serve those communities.

Road Space

Larger automated delivery vehicles that operate on public streets could have an impact on the usage of road space, including bike lanes. The traffic flow impacts of automated delivery vehicles will depend on a variety of factors (e.g., size, speed, driving behaviors, and stop frequency and duration) and are the subject of some debate. Such congestion impacts may vary significantly by use case and

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92 EMCINS. (2020). “Tech Sheet – Sidewalk Design ADA Considerations.” EMC Insurance Companies. Accessed June 10, 2020. <http://www.emcins.com/Docs/Risk/TechSheets/Tech_Sidewalk_Design_ADA_Considerations_20110510.pdf>.

93 Ibid. FHWA. (2003).

94 Shoup, D. (2010). “Fixing Broken Sidewalks.” ACCESS Magazine, 1(36). April 1, 2010. <https://escholarship.org/content/qt57w7z0nk/qt57w7z0nk.pdf>.

95 Maxie, R., Melanson, K., Byers, S., Martin, T., Burns, E., Davis, M., and Fegley, C. (2018). “SDOT Sidewalk Condition Assessment Report.” Seattle Department of Transportation. April 5, 2018. <https://www.seattle.gov/documents/departments/sdot/about/sidewalkassessexecsummary_4_6_2018r5.pdf>.

96 Austin. (2016). “City Of Austin: Sidewalk Master Plan / ADA Transition Plan Update.” City of Austin. June 16, 2016. <https://austintexas.gov/sites/default/files/files/public_works/street_%26_bridge/sidewalk_mpu_adopted_06.16.2016_reduced.pdf>.

97 PBOT. (2017). “Asset Status + Condition Report FY 15-16” Portland Bureau of Transportation. October 2017. <https://www.portlandoregon.gov/transportation/article/666967>.

implementation.[98] Some automated delivery vehicles operate at lower speeds (e.g., 15 mph maximum speed), which could be an issue for other traffic, though low speeds may be less of an issue in urban areas where traffic volume is heavy and average traffic speeds are low. Many implications are currently unknown, but visibility of smaller automated delivery vehicles could be a key issue for drivers and other road users (e.g., bicyclists and pedestrians).[99]

Curb Space

In many cities, curb space must serve competing uses: parking, bus shelters and passenger loading for transit buses, package and freight delivery, and loading and unloading for taxis, ride-hail vehicles, and others. Automated delivery vehicles concepts in urban areas may use curb space for delivery drop-off and pick-up, which could further increase demand, especially for business models where a human recipient must meet the vehicle to complete the transaction. To fully understand the curb space demands of automated delivery vehicles, more information (e.g., vehicle size and average park time) is needed.

Currently, drivers often choose to park illegally (e.g., double-park) when there is a lack of available curb space, or if the delivery point is distant from legal parking locations. Parking shortages can increase delivery time and cost, and illegal parking may increase local traffic congestion and create additional safety risks for non-motor vehicle road users (e.g., bicyclists and pedestrians).[100]

In order to reduce such traffic and safety problems, local officials may actively seek and implement curb space management strategies to accommodate commercial deliveries. One study sought to understand the key factors that influence the operation of urban pick-up and delivery of goods.[101] That research found that a holistic approach to identify key factors and information on delivery attributes (e.g., delivery schedule, nature of the goods, and drop-off locations) and facilities characteristics (e.g., dimension of the sidewalk, slope and conditions, and location and dimensions of the building entrances) could be useful for policymakers to develop more informed urban freight policies. Dynamically managing curb space use could also play a role in improving the efficiency of delivery services; this approach relies on detailed information on parking supply and demand, including time and location.

Several cities are partnering with companies to generate detailed neighborhood curb maps, including Denver, CO; Los Angeles, CA; San Francisco, CA; San Diego, CA; and Washington, DC.[102] While such

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[98] Bernhard, F. (2015). “The Effect of Autonomous Vehicles on Traffic.” Autonomous Driving: Technical, Legal and Social Aspects. Pages 317-334. Edited by Maurer M. Gerdes J. C., Lenz B., Winner H.

[99] Ibid. Penn, B., Lewis, J., and Anderson-Hall, K. (2019).

[100] Shaver, K. (2019). “Study: Allowing delivery drivers to reserve curb space reduces double-parking.” The Washington Post. November 17, 2019. <https://www.washingtonpost.com/local/trafficandcommuting/study-allowing-delivery-drivers-to-reserve-curb-space-reduces-double-parking/2019/11/17/8e569866-062f-11ea-ac12-3325d49eacaa_story.html>.

[101] Butrina, P., Girón-Valderrama, G., Machado-León, J.L., Goodchild, A., and Ayyalasomayajula, P.C. (2017). “From the Last Mile to the Last 800 ft. Key Factors in Urban Pickup and Delivery of Goods.” Transportation Research Record: Journal of the Transportation Research Board, No. 2609, 2017, pp. 85–92.

[102] Small, A. and Bliss, L. (2019). “The Race to Code the Curb.” Bloomberg CityLab. April 2, 2019. <https://www.citylab.com/transportation/2019/04/smart-cities-maps-curb-data-coord-sidewalk-tech-street-design/586177/>; and Glambrone, A. (2019). “Designated curbside space for deliveries and taxis reduces

studies are useful to understand current curb-asset utilization and the impacts of policies related to curb usage (e.g., designated pick-up and drop-off zones), such information will also be important for future efforts to manage curb space usage in real time. The International Organization for Standardization (ISO) has recently initiated work to develop standards needed to support real-time operation of sidewalks and curbs.[103]

Network Impacts Modeling and Analysis

Because automated delivery vehicles may vary in size and driving patterns, when compared to both other automated vehicles and other conventional delivery vehicles, they may have different impacts on traffic networks. There are many different tools and approaches to understand and evaluate network impacts. Mapping curb space and usage is one method, but other modeling and simulation methods can be used to explore the potential economic, social, and environmental impacts of automated delivery vehicles on infrastructure.

In one study, the authors developed a novel model to estimate the delivery time and number of customers served utilizing a combination of automated sidewalk delivery robots and an automated mothership van.[104] The authors used the model to analyze delivery time, cost, and on-road vehicle miles traveled compared to conventional deliveries. Another analysis used a mixed-integer programming model to examine the effect of a two-tier urban freight delivery service on reducing operational costs of last-mile deliveries.[105]

Modeling tools, such as agent-based or system dynamics models, can be used to help identify new issues (e.g., pedestrian safety, sidewalk congestion, and illegal parking behavior), which could emerge under various automated delivery vehicle scenarios. Future modeling work could also evaluate the evolution of these new technologies, understand how they can complement or replace conventional vehicles, and quantify their distinct impacts on sidewalk space, road space, and curb space.

double parking and U-turns: study." Curbed, Vox Media. November 15, 2019. <https://dc.curbed.com/2019/11/15/20966562/dc-curb-space-deliveries-taxis-rideshare-study>.

[103] Grush, B. (2020). "ISO/TC204/WG19/TR4448 - Sidewalk and Kerb Behaviour for Automated Vehicles: Arriving, Stopping, Parking, Waiting, and Loading." Harmonize Mobility. March 3, 2020. <http://endofdriving.org/wp-content/uploads/2020/03/1-Sidewalk-Kerb-Standard-invitation-Q1-2020.pdf>.

[104] Ibid. Jennings, D., and Figliozzi, M.A. (2019).

[105] Bakach, I., Campbell, A., and Ehmke, J. (2019). A Two-Tier Urban Delivery Network with Robot-based Deliveries. Working Paper No. 1., Otto von Guericke University Magdeburg, Faculty of Economics and Management.

Chapter 6. Local Testing and Deployment Considerations

The rapid emergence of automated delivery vehicles has raised both technical and institutional questions in the private and public sectors. When discussing concerns related to automated delivery vehicles, stakeholders highlighted a range of issues, including interactions with other road users, mobility and congestion, equity and access, and data sharing. Many of these issues are not unique to automated delivery vehicles, but are common to many automation concepts.[106]

In some cases, the nature of the delivery service may lead to additional considerations specific to automated delivery vehicles. This chapter will briefly discuss these, as informed by stakeholder interviews with local government representatives.

Early Engagement: In recent years, engagement with local governments by technology developers in a number of fields—TNCs, electric scooters, and automated delivery vehicles—has varied. Interviewees noted that there may be significant interaction and collaboration in advance of a pilot, often including public meetings or other venues to solicit the opinions of local residents. Conversely, sometimes the host community learns about the pilot through a press release or media coverage, with no prior notice. Host communities generally expressed a desire to engage informally early on in the process with companies that would like to test their automated delivery vehicles locally.

Learning from Previous Technology Deployments: Several interviewees noted that they are adapting local policies designed to address TNCs or micromobility may serve as a foundation for the management of automated delivery vehicles. In cases where official pilot programs have been approved by local governments, local governments may set limits on the number of vehicles used or identify specific, limited areas and hours for operation. In many cases, operations require the presence of a chaperone or operator who can provide assistance to the end-user or control the vehicle, as appropriate.

Alignment with Local Goals: While goals vary by community, interviewees commonly identified relevant priorities such as reduced traffic congestion, reduced emission of greenhouse gases, improved availability of fresh groceries in underserved areas, and improved data on infrastructure condition and usage. The ability of automated delivery vehicles to address these goals is unproven. Host communities may wish to consider if there are relevant performance metrics to include in pilot projects to help assess the alignment of new technologies with existing community goals.

Competition for Use of the Public Right-of-Way: As discussed in Chapter 5, public rights of way such as sidewalks, bicycle lanes, and roadways are limited, and in some areas there is significant competition for their use (e.g., pick-up and drop-off for TNCs and transit vehicles, parking, deliveries, and other uses). Finally, walkability and the pedestrian environment are often cited as key, if subjective, components of

[106] For discussion of automation in general, see "Automated Driving Systems 2.0: A Vision for Safety" and "Preparing for the Future of Transportation: Automated Vehicles 3.0" documents.

livability. Some interviewees raised concerns that the introduction of automated delivery vehicles into pedestrian spaces would create intangible negative impacts, which may discourage their use by people.

Data: Local government interviewees suggested that automated delivery vehicles could provide data to improve understanding of local transportation patterns or improve availability and quality of sidewalk condition and usage data. However, it is not clear if the data collected by technology developers aligns with the needs of local communities and there were further questions regarding appropriate data formats. To improve collaboration, some interviewees suggested that a common list of data elements and a technical specification for their format could help enable cities to perform benefit evaluation and help cities and companies to work together. In the case of Kiwibot, the firm operates its sidewalk delivery robots in San Jose, CA and provides data to the city via the Mobility Data Specification (MDS), which is used by many cities to track shared micromobility vehicles, such as scooters.[107]

Equity: As with existing transportation services and other emerging transportation technologies, automated delivery vehicle services may result in equity concerns related to limited access for certain communities or users. Some of these concerns can be operationally identified and addressed (e.g., by companies offering equal service across a metropolitan area, regardless of race or class differences between zip codes, or adjusting service fee structures and payment methods to make the service useful to lower-income and unbanked communities). Other equity concerns may require a concerted technology focus on preventing differential safety and accessibility impacts; for example, by applying universal design principles to the design of the HMI for package retrieval. Automated delivery vehicles may provide potential equity benefits (e.g., improved access for members of disability communities and citizens who live in “food deserts”). On the public sector side, as State and local governments begin to consider policies related to how automated delivery vehicles can be tested and later integrated into the transportation system, there may be opportunities to encourage equity in automated delivery vehicle services.

[107] Ibid. Korosec, K. (2020). “Kiwibot Delivery Robots Head to San Jose with New Partners Shopify and Ordermark.”

Chapter 7. Conclusion

This report describes current conditions in testing and deployment of automated delivery vehicles. It also identifies many of the challenges currently facing the industry that must be resolved to enable more useful services and broader deployment. Key findings include:

- **There is broad interest in the topic:** A variety of stakeholders are engaged in developing and testing vehicles, and many are moving forward with pilot projects that operate on public infrastructure (e.g., roadways or sidewalks). Several pilots are currently operating; as these companies gain experience and further develop their prototypes, they are exploring options to expand existing pilot projects (e.g., geographically, in terms of fleet size, or in terms of customer base), operate similar pilots in new host communities, or address new delivery use cases. Automated delivery vehicles have received increased attention during the COVID-19 public health emergency due to some of their potential operating advantages.
- **Vehicle design is still evolving:** Most automated delivery vehicles are in the testing phase or earlier stages of development. Many systems have somewhat limited technical capabilities and may require human intervention from time to time.
- **Final service models have yet to be determined:** Current automated delivery vehicle activity includes a range of service models that address the middle-mile, last-mile, and final-50-feet. Depending on the evolution of capital and operational costs, vehicle capabilities, customer acceptance, and other factors, some service models may be practical and spread widely, while other service models are less viable. In some cases, a service model may be practical for one vehicle type, but may not work for another vehicle type due to technical or institutional challenges.
- **Teleoperation capabilities are necessary for certain concepts:** While the use of remote monitoring and teleoperation may be important for some automated vehicle concepts, automated delivery vehicles that preclude an on-board operator (e.g., sidewalk delivery robots and other vehicles with novel designs) highlight the importance of remote human monitoring and teleoperation. The number of vehicles that a remote operator can monitor simultaneously has a strong relationship to costs and the business case for certain concepts.
- **State and local governments are at an early stage of policy development:** While some States have passed statewide enabling legislation, there is very little practical experience to inform policy development today. As technologies and operational models mature, policymakers would benefit from analysis of potential benefits (e.g., improved traffic, expanded access to goods) and potential negative impacts (e.g., traffic congestion, erosion of pedestrian space, inequitable access).

As freight movement patterns continue to respond to broader technological and cultural shifts, every stage of delivery is changing, including the middle-mile, last-mile, and final-50-feet phases. While today's automated delivery vehicles face many challenges for broader deployment, continued interest and investment in this area will fuel further development, testing, and deployment activities. This document provides background on automated delivery vehicle and service concepts, industry trends and activities, and common challenges. Many uncertainties exist: further research throughout the world will help inform this field and determine future directions for automated delivery vehicles.

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Appendix A. Out-of-Scope Concepts

There are also several delivery concepts that use automation or remote monitoring and operation that were identified during the research process, but that are considered outside of the scope of this paper. These concepts include heavy-duty commercial trucks, unmanned aircraft systems (UAS), indoor robots, airport baggage tractors, and underground delivery systems. Each of these out-of-scope topic areas is explained in the following bullets.

- **Heavy-duty commercial trucks:** There has been a substantial amount of investment in automation for larger commercial vehicles (i.e., Class 8 semi-trucks) from companies such as Daimler, Embark Trucks, Ike, Kache.ai, Kodiak Robotics, Locomation, Peloton, PlusAI, Pronto, TuSimple, Volvo, and Waymo.[108] Many of these companies are testing vehicles on public roads, with some making actual deliveries for customers. However, these larger vehicles are typically operated in long-haul highway trips rather than last-mile, urban deliveries, and are therefore excluded from the scope of this research and not covered further.
- **Unmanned aircraft systems (UAS):** There has been substantial interest and investment in UAS—also known as unmanned aerial vehicles (UAVs) or more colloquially as “drones”—from companies such as Airbus, Alphabet (Project Wing), Amazon (Prime Air), DHL, FedEx, Flytrex, Matternet, Uber (Elevate), UPS, and Zipline.[109] This paper addresses ground vehicles that operate in the public right-of-way (including sidewalks), while UAS operate in airspace regulated by the Federal Aviation Administration (FAA). UAS are therefore excluded from the scope of this research, except where identified as a potential component of combination models that include road-based automated delivery vehicles. Relevant research related to UAS was considered, especially in regard to remote monitoring and teleoperation.
- **Indoor robots:** While many companies have developed indoor service robots for a variety of purposes, some companies, including Intenxiv, LG Electronics, Pudutech, Savioke, and ST Engineering (Aethon) are producing robots that perform indoor delivery functions in hospitals,

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hotels, and offices.[110] Other companies, such as 6 River Systems, Clearpath Robotics, Fetch Robotics, GreyOrange, Mobile Industrial Robots, and Waypoint Robotics, are producing robots to move items around factory floors and warehouses.[111] These robots operate in relatively controlled environments compared to road vehicles, and their use is regulated by the Occupational Safety and Health Administration (OSHA). Because their operation is outside USDOT jurisdiction, they are excluded from the scope of this report.

- **Airport baggage tractors:** Because airport tarmacs have a limited geographic extent, highly coordinated traffic, and limited vehicle access, development of automated airport baggage tractors has become an area of interest for multiple companies. Some of these companies (e.g., EasyMile, Navya, and ST Engineering)[112] have already developed ADS for low-speed automated shuttles, and automation of baggage tractors represents an opportunity to transfer that technology to a new vehicle format. Other companies involved in airport logistics, such as Vanderlande, are developing automation systems to improve over existing processes.[113] Because their operating environment is not applicable to vehicles operating in the public right-of-way, automated baggage tractors are excluded from the scope of this research.
- **Underground/tunnel delivery systems:** There are some companies, including Amazon, Cargo Sous Terrain, and Mole Solutions, with concepts for automated delivery solutions that would operate in dedicated underground tunnels.[114] Such concepts are not without precedent, as previous companies, such as the Chicago Tunnel Company and the Post Office Railway in London have used underground tunnel delivery in the past. Such systems would operate in highly controlled environments, but would be slow to scale due to the high costs associated with creating the infrastructure needed for operation. Because these vehicles have uniquely different technical and institutional challenges than other ground-based automated delivery vehicles and would not operate in the public right-of-way, they are excluded from the scope of this research.

[110] Walsh, N. (2018). “The Next Time You Order Room Service, It May Come by Robot.” New York Times. January 29, 2018. <https://www.nytimes.com/2018/01/29/travel/the-next-time-you-order-room-service-it-may-come-by-robot.html>; Deyle, T. (2017) “Why Indoor Robots for Commercial Spaces Are the Next Big Thing in Robotics.” IEEE Spectrum. March 1, 2017. <https://spectrum.ieee.org/automaton/robotics/robotics-hardware/indoor-robots-for-commercial-spaces>.

[111] Edwards, D. (2018). “30 automation solutions for warehouses and supply chain operations.” Robotics & Automation News. June 29, 2018. <https://roboticsandautomationnews.com/2018/06/29/briefing-robotics-and-automation-in-logistics-30-solutions-for-logistics-and-supply-chain-operations/17997/>.

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Appendix B. SAE Levels of Automation

This report refers to automation with respect to the SAE taxonomy (SAE Standard J3016). Table B-1 provides descriptions of the SAE levels of automation. Note that SAE J3016 does not apply to sidewalk delivery robots.

Table 3. SAE Levels of Automation

Level	Name	Narrative Definition	Sustained Lateral and Longitudinal Vehicle Motion Control	Object and Event Detection and Response (OEDR)	Dynamic Driving Task (DDT) Fallback	ODD
0	**No Driving Automation**	The performance by the driver of the entire DDT, even when enhanced by active safety systems.	Driver	Driver	Driver	n/a
1	**Driver Assistance**	The sustained and ODD-specific execution by a driving automation system of either the lateral or the longitudinal vehicle motion control subtask of the DDT (but not both simultaneously) with the expectation that the driver performs the remainder of the DDT.	Driver and System	Driver	Driver	Limited
2	**Partial Driving Automation**	The sustained and ODD-specific execution by a driving automation system of both the lateral and longitudinal vehicle motion control subtasks of the DDT with the expectation that the driver completes the OEDR subtask and supervises the driving automation system.	System	Driver	Driver	Limited
3	**Conditional Driving Automation**	The sustained and ODD-specific performance by an ADS of the entire DDT with the expectation that the DDT fallback-ready user is receptive to ADS-issued requests to intervene, as well as to DDT performance-relevant system failures in other vehicle systems, and will respond appropriately.	System	System	Fallback-ready user (becomes the driver during fallback)	Limited
4	**High Driving Automation**	The sustained and ODD-specific performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene.	System	System	System	Limited
5	**Full Driving Automation**	The sustained and unconditional (i.e., not ODD-specific) performance by an ADS of the entire DDT and DDT fallback without any expectation that a user will respond to a request to intervene.	System	System	System	Unlimited

Adapted from "Table 1 - Summary of Levels of Driving Automation" from SAE 2018

Appendix C. List of Interviewees

Formal Company Interviews

- Amazon
- Bedestrian
- Continental
- Cruise
- Gatik
- Kiwibot
- Nuro
- Robomart
- ThorDrive
- TwinswHeel
- Udelv

Formal Community Interviews

- Ann Arbor, MI
- Boston, MA
- Los Angeles, CA (LA Metro)
- San Francisco (SFMTA and SFDPW)
- Seattle, WA (Seattle DOT)
- Washington, DC (District DOT)
- West Hollywood, CA

Formal Academia Interview

- Dr. Andres Sevtsuk (Massachusetts Institute of Technology)
- Dr. Renia Ehrenfeucht (University of New Mexico)

Conference/Trade Show Discussions

- Agility Robotics
- AutoX
- E-Novia (YAPE - "Your Autonomous Pony Express")
- Ford
- Postmates
- Refraction
- Robby

Conference/Trade Show Discussions (Continued)

- ThorDrive
- Toyota
- TwinswHeel

Appendix D. Tables of Companies by Concept Category

Table 4. Companies with Wheeled Sidewalk Delivery Robots

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
Alibaba (Cainiao)	G Plus	China	(5/2018)
Amazon	Carry & Scout	United States (WA)	(6/2019)
Bedestrian	B1 & B2	United States (MI)	(5/2019) Beaumont Hospital (4/2020) University of Michigan
Cartken		United States (CA)	(2/2020)
E-Novia	YAPE	Italy	(7/2017)
Effidence	EffiBOT & PostBOT	France	(6/2016) Deutsche Post DHL
Eliport		Spain	(3/2018)
FedEx	Roxo	United States (NH)	(2/2019) DEKA R&D Corp
GT Technology	GT AI Mobile Vending Store	Singapore	(3/2020)
Hakobot		Japan	(6/2019)
Idriverplus	Idriverplus Delivery Robot	China	(3/2020)
Kiwi	Kiwibot	United States (CA)	(9/2017) UC Berkeley restaurants (2/2020) University of Denver (3/2020) University of Medellin (3/2020) Shih Hsin University
Marathon Robotics	DOM	Australia	(3/2016) Domino’s
Marble	Scrappy	United States (CA)	(4/2017) Yelp Eat24

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
Meituan		China	(7/2018)
Piaggio Fast Forward	Gita	United States (MA)	(1/2017)
Postmates	Serve	United States (CA)	(12/2018)
Robby Technologies	Snackbot	United States (CA)	(1/2019) PepsiCo - Hello Goodness
Segway-Ninebot	DeliveryBot X1	United States (NH)	(8/2019)
Starship Technologies		Estonia	(1/2017) Postmates & DoorDash (3/2017) Domino’s (1/2018) Intuit (1/2019) George Mason Univ. (8/2019) Universities of Northern Arizona Pittsburgh, & Purdue (2/2020) UC Irvine (3/2020) Broad Branch Market
Teleretail (Aitonomi)	Pulse 1	Switzerland	(9/2017) Thyssenkrupp (8/2018) Swiss Post (3/2019) Albert Heijn
Toyota	Micro Palette, DSR, & HSR	Japan	(7/2019)
TwinswHeel	TwinswHeel Droid	France	(1/2020) Valeo
Yandex	Yandex Rover	Russia	(11/2019)
Zhen Robotics	Little Yellow Horse	China	(7/2018) Suning
ZMP	CarriRo Deli	Japan	(7/2017) Ride On Express

Source: USDOT Volpe Center 2020

Table 5. Companies with Legged Sidewalk Delivery Robots

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
Agility Robotics	Digit	United States (OR)	(5/2019) Ford
ANYbotics	ANYmal	Switzerland	(1/2019) Continental
Boston Dynamics	Spot & Pick/Handle	United States (MA)	(6/2017) SoftBank
Ghost Robotics	Vision & Wraith	United States (PA)	(10/2018)
Unitree Robotics	Laikago	China	(10/2017)
Unsupervised.AI	Aida	France	(4/2018)

Source: USDOT Volpe Center 2020

Table 6. Companies with Conventional Design Automated Delivery Vehicles

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
AutoX	Lincoln MKZ	China	(8/2018) DeMartini (8/2018) GrubMarket
Bosch	StreetScooter Delivery Van	Germany	(4/2020) StreetScooter
Boxbot	Polaris GEM	United States (CA)	(6/2019) OnTrac
Cruise Automation	Chevrolet Bolt	United States (CA)	(1/2019) DoorDash (4/2020) San Francisco Marin Food Bank & SF New Deal
Ford	Ford Fusion & Ford Transit Connect	United States (MI)	(8/2017) Domino's (2/2018) Postmates (11/2018) Walmart
Gatik	Ford Transit Connect	United States (CA)	(7/2019) Walmart (5/2020) Planet M / MEDC
Hyundai-Aptiv Driving Joint Venture	BMW 5 Series	United States (MA)	(5/2020) Clark County, NV - Delivering with Dignity Program

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
Nuro	Toyota Prius & Nissan Leaf	United States (CA)	(6/2018) Kroger - Fry's Food (12/2019) Walmart
Optimus Ride	Polaris GEM	United States (MA)	(4/2020) Paradise Valley Estates (5/2020) The Yards, Bluejacket, Pathways to Housing DC, & Van Ness Elementary School
Oxbotica	CargoPod	United Kingdom	(12/2014) TRL (6/2017) Ocado Technology
Pony.ai	Hyundai Kona	United States (CA)	(4/2020) Yamibuy
ThorDrive	Ford Transit Connect	South Korea	(11/2018) Ace Hardware (1/2019) E-Mart
Udelv	Polaris GEM	United States (CA)	(9/2018) BFL, Esperanza, & Narnia (10/2018) Farmstead (1/2019) Walmart (7/2019) H-E-B
Waymo	Chrysler Pacifica	United States (CA)	(7/2018) Walmart (1/2020) UPS
ZF	ZF Innovation Van	Germany	(8/2018)

Source: USDOT Volpe Center 2020

Table 7. Companies with Novel Design Automated Delivery Vehicles

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
Academy of Robotics	Kar-go	United Kingdom	(7/2019)
Aurrigo (RDM)	PodZero	United Kingdom	(1/2018)
Avrora Robotics	VendBot	Russia	(9/2018) Baskin Robins
Cleveron	Lotte	Estonia	(12/2018)
Cool High Technology	KuGaea Kun	China	(4/2020)
DroidDrive	Ducktrain	Germany	(4/2020)
EasyMile	EZ10	France	(10/2016) Acando (10/2016) Kolonial.no (6/2020) Growing Home & U.S. Ignite
Einride	T-pod	Sweden	(6/2017)
EIT Digital	LMAD	Belgium	(11/2019) Futurice, Gim Robotics, BookIt, Picom, Bestmile, & Forum Virium Helsinki
Meituan		China	(7/2018)
Navya	Autonom Shuttle	France	(4/2020) Jacksonville Mayo Clinic (4/2020) Orlando VA Medical Center
Neolix	Neolithic	China	(7/2019) Noon
Nuro	R1 & R2	United States (CA)	(6/2018) Kroger - Fry’s Food (6/2019) Domino’s (12/2019) Walmart (4/2020) Sleep Train Arena & San Mateo County Event Center (5/2020) CVS

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
Rakuten		Japan	(11/2018) Jingdong - JD
Refraction	REV-1	United States (MI)	(12/2019) Miss Kim, Belly Deli, Tios Mexican Café, & Chow Asian Street Food (5/2020) Produce Station
Renault	EZ-Pro	France	(9/2018)
Robomart		United States (CA)	(1/2019) Stop & Shop
Toyota	e-Palette	Japan	(1/2018) Pizza Hut & Amazon
Unity Drive Innovation	UDI Hercules	China	(2/2020)
Valeo	Valeo eDeliver4U	France	(1/2020) Meituan

Source: USDOT Volpe Center 2020

Table 8. Companies with Combination Automated Delivery Vehicle Concepts

Company	Vehicle Name(s)	Headquarters	Announcement Date & Partners
Continental / ANYbotics	CUbE / ANYmal	Germany / Switzerland	(1/2019)
Daimler / Starship Technologies	Sprinter Van	Germany / Estonia	(9/2016)
Ford / Agility Robotics	Ford Transit Connect / Digit	United States (MI) United States (OR)	(5/2019)
Workhorse	Delivery Truck / HorseFly	United States (OH)	(2/2017) UPS

Source: USDOT Volpe Center 2020

Appendix E. Automated Delivery Vehicles and COVID-19 Response

In the wake of the COVID-19 public health emergency, businesses in cities around the world had to close or adjust to new operating constraints. Stores that were able to stay open limited the number of occupants or used other methods to encourage social distancing. Restaurants closed their dining areas and focused on takeout or delivery. Many restaurants, grocery stores, and other retail operations had already been working to incorporate new delivery platforms and experimenting with new services; however, the constraints of the public health emergency dramatically accelerated the evolution of business models.[115] During this time, many automated vehicle companies suspended testing operations, especially those with passenger operations. Many companies testing automated delivery vehicles, on the other hand, continued some of their testing operations, making deliveries to real customers, and often adapting their operations to address the needs of those using their services. In addition, some companies that had been testing automated vehicles for passenger service converted their vehicles to delivery service.

Some observers have noted automated vehicles could have played a larger role in making deliveries during the public health emergency, given the increased demand for delivery, the desire to minimize interactions between delivery drivers and recipients, and reductions in vehicle traffic that could make operating environments less challenging and increase the acceptability of lower-speed automated delivery vehicle operations.[116] The main challenge to broader use of automated delivery vehicles is that the companies developing such technologies are in the prototype testing phase or earlier stages of development. To the extent that some companies may have vehicles that are technically capable of providing useful delivery service, they have relatively few of those vehicles, and there is limited capacity to quickly produce more of them.

Despite the relatively early stage of technological development, some companies tried to use their vehicles to help during the public health emergency. This is especially true in China, where manufacturer Neolix is receiving hundreds of orders and working to ramp up production.[117] Multiple companies are

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[115] Yaffe-Bellany, D. (2020). “These Days, Even a Michelin Star Chef Has to Sell Takeout.” New York Times. March 30, 2020. <https://www.nytimes.com/2020/03/30/business/coronavirus-restaurants-delivery.html>.

[116] Ibid. Templeton, B. (2020); and Ibid. Beans, C. (2020).

[117] Tian, Y. “Driverless Delivery Van Startup Sees Demand Surge Amid Outbreak.” Bloomberg. March 8, 2020. <https://www.bloomberg.com/news/articles/2020-03-08/they-won-t-catch-the-virus-so-chinese-robovan-maker-s-sales-jump>; and Szymkowski, S. (2020). “Coronavirus highlights strengths of self-driving delivery vehicles.” Roadshow by CNET. March 18, 2020. <https://www.cnet.com/roadshow/news/coronavirus-self-driving-delivery-vehicles-china/>.

operating automated vehicle fleets to make deliveries while reducing exposure between humans.[118] Meituan Dianping is delivering groceries in Beijing and is operating on public roads for the first time. The company's vehicles can carry three to five orders at a time. Jingdong (JD.com) is using automated vehicles to deliver medical supplies to Wuhan Ninth Hospital and groceries to nearby communities. Shenzhen-based startup Unity Drive Innovation is using an automated van in the cities of Shenzhen, Suzhou, and Zibo, where the vehicles deliver meals to checkpoint workers and spray disinfectant near hospitals.[119]

In the United States, many companies temporarily shut down their automated vehicle operations, especially those that provided rides for passengers.[120] While some companies focused on automated delivery vehicles also suspended testing, others continued operations, in particular, those that were making deliveries to customers. Some companies with automated vehicle pilots adjusted their operations to support COVID-19 response efforts, either by offering contactless delivery of meals, groceries, or other essentials, or by integrating into the healthcare supply chain. Most of the companies using automated vehicles for delivery operations had already been focused on goods movement, but some companies adapted their passenger operations for goods movement in response to the challenges posed by COVID-19.

Kiwibot has continued using its sidewalk delivery robots for food delivery operations. In addition, in mid-March, the company began delivering masks, antibacterial gels, and other hygiene-related products in both Berkeley, CA and Denver, CO.[121] The company also announced that it would activate fleets in outside of the United States (in Columbia and Taiwan), where it will deliver a broad range of products.

On March 25, 2020, the Broad Branch Market in the Chevy Chase neighborhood of Washington, DC began making deliveries with four delivery robots from Starship Technologies.[122] Though the pilot had been in the planning stage for a year, Starship Technologies had been concentrating its pilot efforts on university campuses until universities began sending students home due to the health crisis. Initially, delivery is free for customers, but it is available in a limited service area, with constraints based on battery range, inability to cross major roads, and local regulations (the vehicles do not have permits to operate in Maryland). As of April 1, 2020, Broad Branch Market closed its doors to in-store shopping and shifted its operations to delivery or pick-up orders only.[123] In addition to its operations in Washington, DC, Starship

[118] Hu, M. (2020). "China's e-commerce giants deploy robots to deliver orders amid coronavirus outbreak." South China Morning Post. February 21, 2020. <https://www.scmp.com/tech/e-commerce/article/3051597/chinas-e-commerce-giants-deploy-robots-deliver-orders-amid>.

[119] Guizzo, E. (2020). "Robot Vehicles Make Contactless Deliveries Amid Coronavirus Quarantine." IEEE Spectrum. April 2, 2020. <https://spectrum.ieee.org/automaton/transportation/self-driving/robot-vehicles-make-contactless-deliveries-amid-coronavirus-quarantine>.

[120] Wiggers, K. (2020). "Coronavirus fears halt autonomous vehicle testing for Uber, Cruise, Aurora, Argo AI, Waymo, and others." VentureBeat. March 17, 2020. <https://venturebeat.com/2020/03/17/coronavirus-halts-autonomous-vehicle-testing-for-uber-cruise-aurora-argo-ai-waymo-others/>.

[121] Chávez, F. (2020). "Kiwibot | Using robots to mitigate Coronavirus." Medium. March 17, 2020. <https://medium.com/@kiwicampus/kiwibot-using-robots-to-mitigate-coronavirus-2ff4c3a8cbe>.

[122] Brunner, R. (2020). "Delivery Robots Come to DC's Broad Branch Market." Washingtonian. March 27, 2020. <https://www.washingtonian.com/2020/03/27/delivery-robots-come-to-dcs-broad-branch-market/>.

[123] Broad Branch. (2020). "Service Update: Delivery/Pick-Up Only Starting April 1st." Broad Branch Market website. Accessed April 1, 2020. <https://www.broadbranchmarket.com/>.

has also expanded its operations in some existing locations (e.g., Fairfax, VA) and initiating pilots in new locations (e.g., Tempe, AZ and Irvine, CA).[124]

Refraction has a delivery robot designed to operate in bike lanes on public roads. The company had been operating in Ann Arbor, MI since fall 2019, but expanded its service since the beginning of the COVID-19 public health emergency, and the number of daily deliveries has quadrupled.[125] Currently the Ann Arbor pilot serves a group of around 500 customers with food from four restaurants and a grocery store. The company currently has eight robots, but has contracted with Roush Industries to increase production and hopes to have an additional 18 delivery robots up and running by the middle of the summer of 2020.

In February 2020, NHTSA granted Nuro a Temporary Exemption from FMVSS for its R2 vehicle, and in April 2020, Nuro received a permit to test it in California.[126] Later that month, Nuro announced that it would use its vehicles to provide contactless delivery of medical supplies, food, and water to front line workers, operating both indoors and outdoors at sites in Sacramento and San Mateo.[127] In Sacramento, Nuro's vehicle operated at Sleep Train Arena, which is a former sports arena that has been converted into an alternative care facility for COVID-19 patients. In San Mateo, the vehicle operated at the San Mateo County Event Center, which has been converted into a multi-purpose facility to assist with COVID-19 response (the facility includes a field hospital, testing site, and alternative housing).

On March 30, 2020, four Navya automated shuttles began making deliveries on the campus of Mayo Clinic in Jacksonville, FL.[128] The shuttles are being used to carry COVID-19 tests from a Mayo Clinic drive-thru testing location to a processing laboratory. The shuttles are currently being operated without on-board attendants or other passengers, though they are closely monitored from a mobile command center. The routes are separate from other pedestrian or vehicle traffic. To enable this service, Mayo Clinic partnered with Jacksonville Transportation Authority, Beep (a shuttle operator), Navya, and BestMile. The Navya shuttles had previously been used in other test activities in Lake Nona and Jacksonville, FL. Beep has also used Navya shuttles to make food deliveries to health-care workers at the Orlando VA Medical Center in Lake Nona.[129]

The Navya shuttles are not the only passenger vehicles that have been repurposed for delivery operations during the public health emergency. In reaction to the crisis, Optimus Ride suspended

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[124] Korosec, K. (2020). "Starship Technologies is sending its autonomous robots to more cities as demand for contactless delivery rises." TechCrunch. April 9, 2020. <https://techcrunch.com/2020/04/09/starship-technologies-is-sending-its-autonomous-robots-to-more-cities-as-demand-for-contactless-delivery-rises/>.

[125] Bigelow, P. (2020). "Bots Bagging More Grocery Runs in Ann Arbor." Automotive News. May 18, 2020. <https://www.autonews.com/technology/bots-bagging-more-grocery-runs-ann-arbor>.

[126] Estrada, D. (2020). "State of California Approves Nuro's Self-Driving Delivery Vehicles for Public Road Operations." Medium. April 7, 2020. <https://medium.com/nuro/state-of-california-approves-nuros-self-driving-delivery-vehicles-for-public-road-operations-943a3cb8266>.

[127] Ibid. Ferguson, D. (2020).

[128] Metro Magazine. (2020). "JTA, Beep, and NAVYA AVs help transport Mayo Clinic COVID-19 tests." Metro Magazine. April 2, 2020. <https://www.metro-magazine.com/mobility/news/738010/jta-beep-and-navya-avs-help-transport-mayo-clinic-covid-19-tests>.

[129] Blanco, S. (2020). "Autonomous People Mover Repurposed As Pizza Mover." WardsAuto. April 28, 2020. <https://www.wardsauto.com/autonomous-vehicles/autonomous-people-mover-repurposed-pizza-mover>.

passenger operations at its pilot sites in California, Massachusetts, New York, and Virginia.[130] Later, the company received a request from management at the Paradise Valley Estates retirement community (its Fairfield, CA pilot site) asking for assistance with on-site delivery. Since residents could no longer congregate in the dining hall due to social distancing requirements, the community needed an evening meal delivery service. Optimus Ride was able to adapt its service to meal delivery operations and has delivered 50–80 meals per day to Paradise Valley Estates residents and noted that it plans to continue these delivery operations while the public health emergency is still ongoing. In May 2020, Optimus Ride, along with its partner, The Yards, announced that it would use its vehicles to make food deliveries to families struggling with food insecurity in Southeast Washington, DC.[131]

EasyMile shuttles have also been repurposed to deliver food to those in need. In Westminster, CO, and EasyMile EZ10 shuttle has been used to deliver food from The MAC recreation center to Growing Home (a local food pantry).[132] The shuttle was used to make two deliveries each morning before the food pantry opened. In Columbus, OH, the Linden LEAP shuttle has been transporting pre-packaged food boxes from St. Stephen's Food and Nutrition Center to residents at the Rosewind Community Center[133].

Similarly, in March 2020, Pony.ai announced that it would suspend operations of automated vehicle pilots that had been providing rides to passengers in the Californian cities of Fremont and Irvine.[134] In mid-April 2020, the company said that it would use its fleet of 10 automated Hyundai Kona sport-utility vehicles to deliver groceries and packages in Irvine. The delivery service will be provided through the Los Angeles-based e-commerce platform Yamibuy. The vehicles are capable of carrying 10–20 orders at a time, and Pony.ai expects each vehicle to deliver approximately 100 orders a day—each vehicle will have a safety operator who will also unload orders and leave them at doorsteps.[135] Pony.ai has also worked with the city of Fremont to distribute meals to a local emergency shelter program.[136]

Like many other automated vehicle developers, Cruise had paused its testing program in March 2020, but in mid-April, the company began working with San Francisco-Marin Food Bank and SF New Deal to

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[130] Optimus Ride. (2020). "Self-Driving Vehicle Systems in a Post COVID-19 World." Optimus Ride website. April 3, 2020. <https://www.optimusride.com/press/self-driving-vehicle-systems-in-a-post-covid-19-world>.

[131] Optimus Ride. (2020). "The Yards to Deliver 5,000 Free Meals Prepared by Bluejacket with Optimus Ride Autonomous Vehicles to DC Families In Need." Optimus Ride website. May 28, 2020. <https://www.optimusride.com/press/the-yards-washington-dc>.

[132] EasyMile. (2020). "Autonomous vehicle delivers food and innovation in the US." EasyMile website. June 15, 2020. <https://easymile.com/autonomous-vehicle-delivers-food-and-innovation-in-the-us/>.

[133] Smart Columbus. (2020). "Three Smart Columbus Mobility Pilots Launch; Seeking Community Participation." Smart Columbus website. July 28, 2020. <https://smart.columbus.gov/news/three-smart-columbus-mobility-pilots-launch>.

[134] Sun, Y. and Goh, B. (2020). "Toyota-backed Pony.ai to offer autonomous delivery service in California." Reuters. April 16, 2020. <https://www.reuters.com/article/us-health-coronavirus-pony-ai/toyota-backed-pony-ai-to-offer-autonomous-delivery-service-in-california-idUSKBN21Y3GK>.

[135] Shepherd, C. (2020). "Pony.ai rolls out self-driving deliveries during lockdown." Financial Times. April 16, 2020. <https://www.ft.com/content/6dbde4af-9db5-4cf6-b996-a70a31052bc1>.

[136] Lanhee Lee, J. and Frandino, N. (2020). "Self-driving vehicles get in on the delivery scene amid COVID-19." Reuters. April 29, 2020. <https://www.reuters.com/article/us-health-coronavirus-self-driving-deliv/self-driving-vehicles-get-in-on-the-delivery-scene-amid-covid-19-idUSKBN22B2LZ>.

deliver meals to local recipients using some of its automated vehicles.[137] In the first eight days of the service, Cruise delivered more than 3,700 meals. As with Cruise's previous automated vehicle testing, its vehicles are staffed by two on-board safety operators. The initial service uses a portion of the Cruise automated vehicle fleet, but the company has noted that it plans to scale depending on demand.

In May 2020, the Hyundai-Aptiv Driving Joint Venture announced that it was working with Delivering with Dignity, a local non-profit organization in Las Vegas, NV, to provide meals to vulnerable families at risk of contracting COVID-19.[138] The effort will use three BMW 5-series cars. The vehicles had previously been used for passenger operations in partnership with Lyft, and as with the passenger operations, all vehicles are manned by a safety operator. The service will provide deliveries from multiple restaurants during weekdays.

[137] Yvkoff, L. (2020). "Cruise's Self-Driving Cars Typically Transport Employees; Now They're Delivering Meals To Those In Need." Forbes. April 29, 2020. <https://www.forbes.com/sites/lianeyvkoff/2020/04/29/cruises-self-driving-cars-typically-transport-employees-now-theyre-delivering-meals-to-those-in-need/#5c8408a52675>.

[138] Wiggers, K. (2020). "Hyundai and Aptiv redeploy autonomous vehicles to deliver meals to vulnerable people in Las Vegas." VentureBeat. May 11, 2020. <https://venturebeat.com/2020/05/11/hyundai-and-aptiv-redeploy-autonomous-vehicles-to-deliver-meals-to-vulnerable-people-in-las-vegas/>.

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