Multimodal Technologies and Interaction

Article

Sharing the Sidewalk: Observing Delivery Robot Interactions with Pedestrians during a Pilot in Pittsburgh, PA

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Abstract: Sidewalk delivery robots are being deployed as a form of last-mile delivery. While many such robots have been deployed on college campuses, fewer have been piloted on public sidewalks. Furthermore, there have been few observational studies of robots and their interactions with pedestrians. To better understand how sidewalk robots might integrate into public spaces, the City of Pittsburgh, Pennsylvania conducted a pilot of sidewalk delivery robots to understand possible uses and the challenges that could arise in interacting with people in the city. Our team conducted ethnographic observations and intercept interviews to understand how residents perceived of and interacted with sidewalk delivery robots over the course of the public pilot. We found that people with limited knowledge about the robots crafted stories about their purpose and function. We observed the robots causing distractions and obstructions with different sidewalk users (including children and dogs), witnessed people helping immobilized robots, and learned about potential accessibility issues that the robots may pose. Based on our findings, we contribute a set of recommendations for future pilots, as well as questions to guide future design for robots in public spaces.

Keywords: sidewalk robots; human–robot interaction; field observations; public robots

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Citation: Weinberg, D.; Dwyer, H.; Fox, S.E.; Martelaro, N. Sharing the Sidewalk: Observing Delivery Robot Interactions with Pedestrians during a Pilot in Pittsburgh, PA. *Multimodal Technol. Interact.* **2023**, *7*, 53. https://doi.org/10.3390/mti7050053

Academic Editors: Marius Hoggenmueller, Martin Tomitsch, Jessica R. Cauchard, Luke Hespanhol, Maria Luce Lupetti, Ronald Schroeter, Sharon Yavo-Ayalon, Alexander Wiethoff, Stewart Worrall and Cristina Portalés Ricart

Received: 2 March 2023
Revised: 20 April 2023
Accepted: 4 May 2023
Published: 17 May 2023

1. Introduction

Personal delivery devices (PDDs), also known as sidewalk delivery robots, are being deployed at an increasing rate in cities around the world [1]. For those intended to move goods such as food and personal items, the robots typically weigh under 350 kg, travel at low to moderate speeds of 45 kph or less, and often share the sidewalk with pedestrians [2]. PDDs have been suggested as a potential technology to improve freight efficiency and reduce carbon emissions while meeting people's increasing demand for rapid delivery [3].

Many PDD deployments within the United States have focused on college campus delivery. While the service remains popular across campuses, prior work has found that the robots may impact pedestrian safety [4]. However, to date, there have been fewer deployments of sidewalk robots on public walkways with more varied terrain and people. Furthermore, there has been little research on how the public may interact with the robots, a noted gap in the research, as college campuses may not represent public spaces as a whole, because they are likely more well-maintained and have a more homogeneous population [4] who may be more likely to accept and desire robot delivery [5].

Despite the lack of testing of PDDs in open, public spaces, government officials have begun to set regulations, often at levels above local government (such lawmaking can sometimes be preemptive of local laws or ordinances by being made at the state level https://www.pml.org/advocacy/local-preemption-in-pennsylvania/, accessed on 13 May 2023). However, local municipalities may wish to better understand how PDDs could impact sidewalk interactions before widespread deployment. Pilot deployments with controlled numbers of robots operating in specific areas could help municipalities understand how pedestrians interact with the robots, the challenges that the robots and pedestrians face, possible service opportunities for local businesses, and the general opinions of city residents around sidewalk robot technology.

To answer understand the potential local impacts of sidewalk robots, the City of Pittsburgh's Department of Mobility and Infrastructure (DOMI), with support from the Knight Foundation, conducted a pilot study of delivery robots operated by the startup Kiwibot [6] between July–December 2021. During the pilot, our research team used ethnographic methods to observe the deployment. Ethnographic methods allow researchers to analyze the practices of stakeholders in sites where formative and exploratory knowledge is needed to understand the applications or effectiveness of new technology [7,8]. Here, observation allowed us to understand the real-world operation of delivery robots on public sidewalks, as well as reactions of and interactions with the public. Our data consists of field notes from regular public meetings, analytic memos from conducting field observations on robot interactions in the public, interviews with people who interacted with the robot, and interviews with key stakeholders from the city and robot operator. Collectively, we leverage this information to understand aspects of the following research questions: (1) What are residents' concerns about the deployment of sidewalk robots? (2) How do people interact with the robots when they are operating on public walkways? (3) What challenges do people and robots face when encountering each other in public spaces?

Our primary findings center around people's knowledge of and the stories they told about the robots, robots becoming stuck along their route and requiring assistance, unanticipated interactions between sidewalk users (e.g., children and dogs), hindrances to traffic, and community members' concerns on how accessibility could be impacted with a wide deployment of sidewalk robots on pedestrian walkways. Based on our observations, we contribute a set of recommended future research and design directions to improve public interactions between sidewalk users and PDDs.

2. Related Work

2.1. Trade-Offs of Shifting Freight Road Traffic to Sidewalks

The "last mile" of goods delivery is regularly considered the most costly and time-consuming leg of shipping, requiring frequent stops to drop off one or few packages at a time. Traffic congestion in dense areas also contributes to the time it takes for a package to reach its destination. Some estimates suggest that last-mile delivery accounts for up to 53% of total shipping costs [9]. In response, vendors have invested in new, automated technologies to improve delivery routing and introduce savings (as compared to standard truck deliveries) [10]. A recent McKinsey & Company report argues that self-driving vehicles and sidewalk robots could reduce last-mile delivery costs by 40% [11]. Jennings and Figliozzi note that sidewalk robots could offer cost and time savings in particular scenarios through the reduction of on-road travel per package delivered [12]. Some models, for example, propose using a "mothership van" as a mobile hub to distribute delivery robots to certain areas where they are then deployed to make individual deliveries. Others use a follower model, whereby robots support delivery staff, using multiple sensors and cameras to track the person and follow their path [13]. Lastly, there is the sidewalk robot model which is oriented around the delivery of goods from nearby restaurants, grocery stores, and pharmacies to people in the local neighborhood.

Alongside discussions regarding cost reduction of goods and parcel delivery, scholars note a series of issues that could arise with the distribution of sidewalk delivery robots, particularly related to pedestrian safety and sidewalk congestion (similar arguments have been made in the popular press since at least 2017 [14]). Scholars have raised concerns that current safety standards for PDDs are not sufficient for public walkways due to the complexities of crowds, social norms, and people's active engagement with robots [15]. Even proponents in the business press suggest "*robots are not appropriate on crowded sidewalks*", due to their inability to manage the unpredictability of pedestrian walkways, climb stairs, and operate without human assistance [1].

Legal scholars and policy experts have also focused recent attention on the public deployment of robots, as commercial entities have increased their investment in piloting them on city streets. Some suggest the movement of robots from manufacturing and fulfillment contexts into public space represents the "*imposition of 'warehouse logic' and values onto society at large*" [9] (p. 5). Others, like Thomasen, highlight a range of concerns around their use including the commercialization of public space, opportunities for heightened surveillance, and how they may privilege members of society who can pay to use or access these new technologies at the expense of those who rely on public walkways to get around [16]. The physical intrusiveness of public robots and data collection associated with their use may reduce the accessibility of public space for some residents.

As Thomasen argues, "*the laws that regulate robots deployed in public space will affect the public nature of that space*", meaning how regulation is written around these devices and their use will have long-standing effects on how residents experience their local communities (as more or less public) ([16], p. 276). The State of Pennsylvania, for example, recently defined sidewalk robots as "pedestrians," ostensibly bestowing them the same legal rights as human occupants [17]. This decision opened questions about their right to sue property owners when sidewalks are impassable, among other protections.

Given the regulatory uncertainty around public robots, it is critical that we further understand how they interact with people, particularly on crowded walkways. In this paper, we build on these growing efforts to understand the potential impacts of sidewalk robots on public space by examining trade-offs and issues introduced by shifting freight road traffic to pedestrian walkways.

2.2. Prior Observations of PDDs in Public Spaces

Although sidewalk delivery robots are actively being deployed in both private and public spaces, there has been relatively little research on how people interact with these robots. The work that does exist has been conducted in two primary ways: (1) Wizard of Oz studies, where researchers place a robot into the public and remotely control it, often to test specific interactions between robots and pedestrians, and (2) observational studies, where researchers document real-world deployments of sidewalk robots in public and describe the interactions that robots have with the public.

2.2.1. Wizard of Oz Studies

Abrams, Platte, and der Putten conducted a Wizard of Oz study in Aachen, Germany, with a remotely controlled sidewalk delivery robot [18]. During their public test sessions, they observed different interactions with people, including children being interested in the robot and wanting to know more and people being opposed to the robot's presence, with one older couple verbally suggesting that the robot should not be allowed. In another study, Vroon et al. explored potential conflicts between people and PDDs through a Wizard of Oz intervention study conducted on public sidewalks in Delft, Netherlands [19]. Their findings showed that even when they deliberately staged a robot that ignored people, it was likely to cause conflict, with people needing to move out of its way. In general, they found that people would observe or take pictures with it, or avoid the robot altogether (this could be a novelty effect as, in general, this work suggests that people were fairly adaptable). Another Wizard of Oz study conducted in Utrecht, Netherlands, observed that many people ignored the robot as they walked by, but some fled [20]. In some cases, fleeing was due to people's dogs; specifically, owners tried to rein in their dogs so that they could keep moving on their journey.

Across these studies, public reactions are varied, some were positive and others negative. Existing work also suggests that sidewalk robots must have some sense of social appropriateness to navigate public spaces, a sentiment echoed by much research on social navigation [21–24]. In our observational study, we sought to document the varied kinds of reactions and interactions residents had with the sidewalk robot deployment. Our goal is to provide information on real-world interaction such that designers and service operators might design appropriate responses, especially in situations where interactions are not pleasant or smooth [25].

2.2.2. Observational Studies of PDDs

During a sidewalk robot pilot on the campus of Northern Arizona University, Gehrke et al. [4] found the robots had several moderate to severe interactions with pedestrians and bicyclists. The team tracked post-encroachment time (PET) and evasive maneuvers (e.g., swerving or stopping) that road users performed to avoid collisions. The authors conclude, "*these new autonomous technologies are disrupting travel*" ([4] (p. 10), finding that many interactions could have a high probability of collision and that pedestrians and bicyclists changed their paths to avoid a collision. Issues were slightly more prominent for cyclists. This was echoed in a survey of students, which found that cyclists were less comfortable sharing pathways with robots. Overall, the observations and survey of students found that more work is needed regarding policies and algorithms for defining how sidewalk robots should navigate to avoid possible collisions with pedestrians.

Another study in Estonia documented four days of observations of sidewalk delivery robots in public. The research found that people had generally positive interactions with robots while on the street and often commented on how cute the robots were on social media [26]. However, heavy snow led many robots to become stuck. In some cases, pedestrians helped the robots by freeing them from the snow. These interactions show sidewalk robots' possible mobility issues during certain situations; however, they also suggest that people might be a resource for helping the robots. Prior work has compiled a checklist for designing robots that ask for help, overall suggesting polite behavior is important [27]. A Wizard of Oz study of what might prompt people to help a stuck robot found passersby were more likely to help a robot that asked for help verbally and was moving (indicating it was stuck but trying to move), though some people felt more empathy for a robot that was beeping [28]. While such helping behaviors may be seen as positive, Dobrosovestnova et al. pose potential ethical issues [26]. They report that some social media comments collected during the Estonian deployment suggest that people were giving free labor to the delivery companies and that the robots were obstructing the public sidewalk due to how often they became stuck. Our observations replicate some of these findings, showing that some people choose to offer help to robots in distress.

2.3. Human–Robot Communication in Public

Robotic communication with people has been studied for different robot types and in different public scenarios. Angelopoulos et al. [29] provide an excellent review of prior work on non-verbal communication for both humanoid and non-human robots in public. Their review of prior studies found that LED light strips may not be entirely interpretable without prior training on what the signals mean [30] and that gaze may be a more understandable signal in communicating a robot's trajectory [31]. Angelopulos et al. motivate their study based on prior work with non-humanoid robots where people did not always interpret strategies such as backing off [32] or moving out of the way [33] correctly and so they proposed the use of deictic arm gestures to increase interpretability [29]. Their findings show that such arm gestures were better at conveying the path a robot would take as opposed to adjusting the robot's gaze alone.

However, in the case of non-humanoid robots, such as those commonly used for sidewalk deliveries, communication through lights or screens is often better. Kannan et al. [34] found that displays with text and more complex graphics were preferred over lights alone, though other research has found flashing lights to be more interpretable, especially when used like turn signals [35]. Alternative strategies of displaying patterned light such as arrows on the ground may also be better than onboard lights [36–38]; however, people may need more training to understand such signals [39].

In a more speculative direction, Lupetti et al. [40] present three kinds of robot communication, (1) a transparent robot to show what is wrong with the robot, (2) a handleable robot to show that the robot can be touched and handled, and (3) a shape-shifting robot that can interact and touch people with a soft body. These ideas for communication suggest the interrelation between robots and pedestrians and are used to consider what a robot 'citizen' (i.e., a robot that is accepted as a part of the community) would be able to communicate. Furthermore, they suggest communication that may engender trust and encourage people to interact positively. Even though the robots in the Pittsburgh pilot were not explicitly designed using these three design concepts, it is valuable to consider when people feel trusting toward robots and if there may be communication interfaces that promote such interactions.

2.4. Key Takeaways from Prior Work

Considering the prior work, the team observed a further need to understand how people interact with robots built specifically to share public walkways. While much advancement has been made around the capabilities of navigation and operation within public spaces [21,23,24], social cues and implicit communication between PDDs and people present additional challenges [15]. While prior work has proposed communication strategies that can improve people's understanding of robot motion through non-verbal cues [34] or might engender trust in and helping of a robot [26,28,40], there is still little work showing how people respond to robot communication during deployments on public walkways. Consider the near collisions PDDs often had with cyclists referenced in Gehrke et al. [4], the fleeing behaviors documented by [20], or the positive and negative aspects of people helping robots that become stuck as seen in Dobrosovestnova et al. [26]. The challenges that occur when PDDs share space with pedestrians call for additional observation of people's actions when encountering robots and their thoughts on comfort, understanding, and safety when sharing the sidewalk. Our research observing a real-world deployment of PDDs on public sidewalks looks to build upon findings from prior Wizard-of-Oz and observational studies to inform the future design of PDDs and policy considerations for robots using the sidewalk.

3. The Pilot

The pilot deployment was conducted by the City of Pittsburgh's Department of Mobility and Infrastructure (DOMI) and developed in conjunction with robotics startup Kiwibot, who supplied and operated the PDDs. Our team from Carnegie Mellon University was permitted to observe the pilot in exchange for support in data collection and analysis of people's interaction with the robot and the deployment process. The purpose of DOMI's pilot was to inform local policies and prepare municipal staff leading up to the widespread deployment of PDDs (spurred by state legislation legalizing their operation), as well as gauge residents' interests in and concerns around the technology. Three local businesses (a library, a small neighborhood pharmacy, and a food truck) across the neighborhoods of Bloomfield, Garfield, and Lawrenceville, were chosen by DOMI as partners and origin points of the deliveries. These specific neighborhoods were preferred because of the density of local businesses and the wide sidewalks in the business district.

The Kiwibot itself is a small sidewalk delivery robot measuring roughly 45 cm $\times$ 45 cm $\times$ 31 cm and weighing 34 pounds without cargo. The robot can travel at a maximum of 6.4 kph (Figure 1). The robot has a digital screen on the front, which displays the phrases, '`Thank You`', '`Autonomous`', and '`Help`' at specific times, as well as various shapes, such as hearts, that mimic eyes. Attached to the bot is a 1.22-meter flag, meant to allow the robot to be seen from a distance.

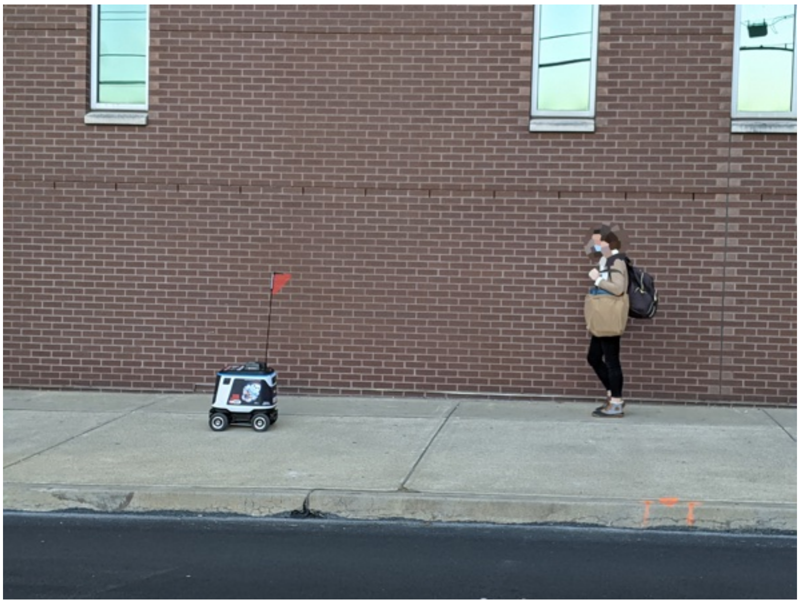

Figure 1. The Kiwibot moving in Pittsburgh after passing a pedestrian on the sidewalk.

The pilot formally began in June 2021 and concluded in December 2021. 10 different PDDs were used throughout the 6-month pilot, however, no more than three were ever active simultaneously. The pilot took a two-phased approach to prepare for deployment. In Phase 1, 1–2 robots were used to map the spaces that the PDDs would be operating in during the delivery period. During the mapping phase, much of the Garfield neighborhood was found to be too challenging to navigate due to cracked or missing sidewalks and obstructions on the sidewalk. Phase 2 focused on gradually operating more robots in public spaces, first with an operator present near the robot, and later with only a remote operator monitoring the device.

It is important to note that many of the deliveries that occurred during the pilot were simulated. Due to low demand for deliveries, only 9 resident-ordered deliveries were placed with the chosen local businesses, while 1400 simulated orders occurred. The simulated orders were generated by Kiwibot to create more interactions between robots and pedestrians. In these deliveries, the PDD still traveled from a starting point to a destination, but no cargo was involved. Pedestrians who saw the PDD during the pilot would have no indication of when a delivery was 'real' or simulated. Furthermore, many of the routes taken were on wider sidewalks or those with lower pedestrian density. To minimize the number of issues, the PDDs were never deployed during heavy rain or snow.

To educate and familiarize the public with PDDs, 10 community outreach events were led by DOMI during the pilot. This included education sessions at Farmers' Markets, youth events, and demonstrations at the pilot's Steering Committee meetings. Residents could also track updates on the pilot through the City's formal website and press releases. In the City's final evaluation of the pilot, it was noted that "early community conversations" proved to be most effective.

During the pilot, there were 17 documented external incidents that involved third parties. These incidents included seven people kicking the robot, three people flipping it or throwing it into a dumpster, one collision with a vehicle, one collision with a seated café patron, and three instances of vandalism such as graffiti and placing a traffic cone on the robot. These incidents were reported both by residents and Kiwibot operators, the former using 9-1-1 and 3-1-1 lines to report complaints.

4. Method

Our research sought to answer the question, "How do people interact with the PDDs over the course of this public pilot?" To answer this, we observed the deployment of Kiwibot delivery robots in the Bloomfield, Lawrenceville, and Garfield neighborhoods of

Pittsburgh, PA, USA from 28 June to 15 December 2021. The first two authors conducted observations of the robots in public. When in the field, the observer would locate themselves along a route that the robot was traveling. The observer would either find a location where they could have a large field of view of the sidewalk, such as a café table, or to walk on the sidewalk through the neighborhood. The observer did not follow behind the robot to avoid being associated with the robot. The observer took pictures of people interacting with the robot from afar. The team observed the robots while they were mapping the sidewalk or conducting simulated deliveries to capture data on pedestrian interactions. Publicly, the 'simulation' was unknown, and pedestrians believed the robot was delivering to real customers. While observing, the team paid attention to various aspects of the interaction between the robot and people. These included how the robot moved along the sidewalk, how the robot interacted with someone when the travel path intersected with a person or a person approached the robot, basic information about the people and their behavior interacting with the robot, and any incidents where the robot was unable to move or needed assistance from a Kiwibot team member. We tracked demographic information of pedestrians, including the use of assistive mobility equipment, direct and indirect interactions with the device, along with proxemics and body language. In total, we observed 25 h of robot operation across 16 field observations. See Appendix A for a detailed observation guide. The observers captured photos and wrote detailed field notes following an ethnographic style of note-taking [41].

The observation team also conducted eight intercept interviews with pedestrians who interacted with or passed by the robots [42]. Interviews lasted no more than 10 min and consisted of questions about people's perceptions and impressions of the robots. We included both Likert scale questions and open-response questions (see Appendix B for the interview guide). We qualitatively analyzed the collected data using affinity mapping to derive a set of insights around pedestrian–robot interactions and to motivate future work around sidewalk robot design and deployment.

5. Results

5.1. Public Knowledge & Folklore

Sightings of a PDD often triggered questions and conversations among pedestrians. People tried to make sense of what they were seeing, often for the first time. When pedestrians were in the company of one another they would frequently share information on what they believed to be the background and purpose of the devices. People engage in sensemaking when the anticipated flow of their environment is interrupted when something surprising happens. Pedestrians who saw a PDD in the company of others exchanged questions without the ability to gather immediate answers or shared theories and unchecked rumors about the robots.

In one case, the PDD moved past three women sitting at a bus stop. The women appeared to have seen the device before as they had both information and questions to offer in the conversation.

> Sitting at the bus stop are three older women, all smoking cigarettes. I (First Author) sat with them. The woman sitting in the middle notices the robot first; she takes her cigarette down by her side, sits up straighter, and leans forward toward the device. She points it out to me and the other two women. The woman says, "Did you know it carries pizza?", then follows with "That seems like an expensive way to deliver pizza." The second woman responds, "Whom does it belong to?" Who owns it?" The first woman says back, "I see it in my neighborhood all the time." The third woman says, "They should be careful with what neighborhood they send it to, not everyone will be kind to it." The second woman replies, "Will it be here for the long haul?"
>
> (Observation, 3 November 2021).

Not only did these women have questions about the device, but in lieu of reliable information, they offered theories instead. As sensemaking is often a social process, these women not only shared out, but also responded and reacted to the information that each provided. They were attempting, as a group, to make sense of the unexpected [43]. As the PDD itself offered no explanation of its existence or purpose, residents filled in the gaps on their own. Though innocuous in this case (carrying pizza), misinformation around the devices and their use could just as easily sow doubt or confusion.

In another observed interaction, two painters moved back and forth between a private home and their van on the street. They saw the device about 6 m away on the sidewalk as it moved in their direction.

> The painter closest to the house leans towards the sidewalk and says, "I'll give you $30 to go pee on it." The other painter on the sidewalk laughed and moved his head to follow the robot as it passed by. "I think they all have cameras on them. They're watching us, and they'll know if we touch it," he said. The painter in the house responds, "I heard they deliver mail from the post office. So dumb." (Observation, 8 November 2021)

While neither claims made were true, each painter offered what they have heard or what they assumed to be true about the PDDs. The device itself offered no additional information on its purpose, either on its physical hardware or through sound (as shown in Figure 2). The top plane of the robot featured a QR Code that, when scanned, directed users to a page on the City of Pittsburgh website providing information on the pilot. To see and scan this code, a pedestrian would have to have been standing directly over the PDD, and the device would have had to have stopped moving long enough for the mobile camera to focus on the code. During our research, we did not observe any pedestrians accessing the QR code.

Without this verified information, pedestrians used context clues to add meaning to their changing environment. Pedestrians who are familiar with their day-to-day environment may seek understanding when a change suddenly occurs. As we observed different groups of people share misinformation with one another, it can be assumed that those who discuss with one group may discuss with another. This may create a chain of misinformation, and without verified interference, these theories continue to spread.

Often when groups of people are together, individuals implicitly work together to reach a shared sense of understanding. They do so by sharing their interpretations of the situation to process the particular situation or event [44]. In this case, their sensemaking was less about discovering what the device was or did, but why it was in their space. As the robotic device was new to them, those observed in this study seemed to attach not only an explanation ("What is it?") but also meaning ("What is its purpose?") to what they observed.

In most of the overheard conversations, at least one pedestrian noted that the device's function was delivery. Many of their questions or assumptions stemmed from that shared fact. It is important to note that in these moments of sensemaking, not all information shared was inaccurate; however, when there was no ground truth, the group was unable to come to a shared conclusion. We observed a group of builders working on the sidewalk on a residential street. When the PDD moved past them, they all stopped to stare at it. They took their phones out to take pictures of the device.

Figure 2. Kiwibot in Pittsburgh, showing only "AUTONOMOUS" on the digital display.

> Construction worker 1 says, "Is this supposed to be delivering something?" Construction worker 2, responds, "I've seen it come up and down this street all day, and it hasn't made a single delivery." Construction worker 1, while still watching the device, "Is someone controlling that?" Construction worker 3 adds, "How many of these are there?" Construction worker 4, while taking a photo says, "It looks so fucking stupid."
>
> (Observation, 3 November 2021).

The conversation represents pedestrians' desire to make sense of the change occurring in their environment. Despite the digital press releases that were shared by the government at the time, it is clear from the observed conversations that many pedestrians were unaware of the pilot with Kiwibot, and have little-to-no prior knowledge of delivery robots.

The act of photographing the device demonstrates a sense of curiosity from the pedestrians. A shared lack of knowledge heightened that curiosity, with workers asking more questions or attempting to observe the device more closely. In this case, the workers shared a sense that the device is meant for delivery, but when Worker 2 asserted that the device has not made any deliveries, their understanding was subverted and more questions are posed. The lack of resolution to the questions ultimately left the workers with a negative sentiment about the PDDs.

5.2. Distractions and Obstructions

The novelty of ground delivery devices also piqued the interest of children. Past research on delivery devices has mostly focused on interactions between adults and robots, but for our research to fully address the public spaces where PDDs exist, we need to consider all humans that are present in those spaces. We observed children inspecting the robot when passing it on the sidewalk. Many children would touch, stare, and block the device in an attempt to understand this interruption in their environment. As shown in Figure 3, a mother and her children were seen interacting with the device.

(**A**) (**B**)

Figure 3. (**A**) The woman and four children approaching a moving PDD, (**B**) the woman and children stop and block the path of the PDD to observe it more closely.

In some incidents, the lack of communication from the PDD inadvertently caused blockages on the sidewalk. To probe the robot and make sense of it, some children stood directly in front. This stopped the device from moving and created an obstacle in the sidewalk for pedestrians.

> A mother and four children approached the bot as it headed toward them. The mother was carrying one child, two were on her left and one on her right side. They slowed down as the bot approached them, and then it stopped when they were about 1–2 feet from the family. The mother placed the child she was carrying on the ground, and all 5 of them circled around the bot, hinging at the waist to see more closely. The smallest child asked, "Why did it stop?!" One of the children reached out to touch it, and the mother said, "Don't touch it, it's not ours." She ushered the kids to continue walking forward, but they did not move. Their eyes and mouths were all open wide and they continued to lean toward the PDD. After about another minute, the mom told them to keep walking, and they did. After walking a few more feet, the smallest child stopped and turned around, looking back at the bot as it rolled on. (Observation, 5 November 2021).

As the children approached the robot, it stopped moving. In doing so, it inadvertently made itself more available to the children to approach and inspect. During this period, the device took no steps to inform their curiosity or guide their actions. Until the mother reprimanded the children for touching the device, it could be assumed that these children did not know how to interact with the PDD. They explored freely because no set norms had been given to them in this context. On the contrary, two eye-like shapes were displayed on the screen, which may have anthropomorphized the device. Assigning human characteristics to the device may have further piqued the children's curiosity, and even aided in the child–robot interaction.

To learn more about and understand the PDD, the children obstructed the path and hindered the PDD's movement. In the aforementioned scenario, four children and one adult have stopped on the sidewalk, effectively creating a hazard for other pedestrians. As the sidewalk became more crowded, and the attention of the pedestrians pulled away from their surroundings and into a singular place, the accessibility of the sidewalk changed (how situations like this might affect pedestrians with disabilities is discussed later in Section 4).

This long-term interaction posed a challenge for the parent or the accompanying adult. While the children appeared to be curious and possibly excited, the parent became frustrated. In this case, the mother had no answer to her children's questions and struggled to regain their focus on the task at hand. The mother made multiple attempts to usher the children away from the robot, but was unsuccessful. In this respect, the parent may not only have been frustrated with the children but with the device. Without communication or guidance from the PDD, the parent was left to their own devices to regain control of the situation. To the parent, the negative sentiment from this interaction may be associated with delivery robots in the long term.

While we observed adults pausing on the sidewalk to view the robot, children were more likely to stop for a longer period of time, effectively abandoning the course they were initially taking. In another observed encounter, two children blocked the path of two PDDs and attempt to push one in another direction. As seen in Figure 4, the children have moved from observing one PDD to blocking the path of a second, incoming device.

> A man and two young boys walk by the PDD, which has been backed up against a wall. The two boys skip over to it, calling to their dad to notice it. The boys stand directly against the bot, which has stopped moving. One boy says "I think it's stuck." Both boys begin to push the PDD but fail to move it easily. The other child says, "I think it's dead." They push and pull the PDD until it's moved about 2 feet. One of the boys sees another PDD moving toward them and runs over to it. The other boy follows, and as they both get close, the bot stops moving. They stand right in front of it, looking directly at the device's face, and press their hands against it. The boys begin talking to the bot, saying, "Hello Robot. Can you hear me? Can you see me?" The father is standing about 4 feet away, watching his sons and looking around the sidewalk. After a minute or two a Kiwibot employee comes over and talks to the family, ending the interaction. (Observation, 9 December 2021).

Though no harm was done in this particular scenario, it is easy to imagine how with the children pushing and pulling the device it could have been damaged, or more problematically the children themselves could have been hurt. The Kiwibot only communicated through various eye shapes and a short list of polite phrases (unless there was an emergency, as described in the following section), which likely invited engagement as it appeared to be social.

The digital display on the device did not show different iconography or words when the children approached it, implying there was no communication method for minimizing crowding or blockage. We hypothesize that should an incident like this occur outside of the pilot, when the PDD is carrying real deliveries, the device will be delayed. Furthermore, if the items the PDD contains are time or temperature sensitive, these blockages would cause issues to the end user (not only the other pedestrians attempting to get by). The PDD was passive in this scenario and did not communicate its own needs, and because of this, the experience of the end user would have suffered if it had been a real delivery.

Figure 4. After observing one robot, two children block the path of another.

Other than children, we also observed dog-robot interactions that caused blockages on the sidewalk. While not all dogs reacted to PDDs passing by, those that did respond did so with overt action.

> A woman is walking two small dogs on the sidewalk, both in front of her. She stops about 5 feet away from a moving robot to take a picture, and as she steps closer, both of the dogs begin to bark. She pulls the leashes back towards her, but the dogs jump forward, continuing to bark. When she begins to move again, she holds the leash tighter against her, pulling the dogs close. She moves onto the street to give space between the PDD and her dogs. As she does this, a cyclist on the street swerves around her. Additionally, two pedestrians who had been walking behind the woman slowed their pace as she negotiated where to walk. The woman turns to me and exclaims, "I'm so curious what it's delivering!" (Observation, 10 November 2021).

> A woman walking a brown dog stops at the corner of the street and watches as a robot crosses from the other end. The dog begins barking non-stop, prompting the woman to say, "I know girl, I see it too." As the bot moves past them, the dog moves towards it and continues to bark. Another pedestrian walking behind the woman slows her pace as she sees the dog barking. She seems to notice the dog first and quickly moves to the inside of the sidewalk so as to not hit the woman

> and dog. The first woman stands still, moving her head to look at the robot as it passes her. (Observation, 1 December 2021).

In both scenarios, the novelty of the PDDs not only affected humans but also their pets. When pets reacted suddenly, their owners seemed to be caught off guard, causing them to stop on the sidewalk or rethink their movements. While owners attempted to minimize interaction between their pets and the PDDs, their movements to do so inadvertently caused obstruction for other pedestrians. Sidewalks have a natural flow as pedestrians pay attention to one another's speed and movements, and act accordingly [12]. However, sudden movements require other pedestrians to re-navigate and adjust their own actions, and if they do not, a collision may occur. We hypothesize that if sidewalk robots are increasingly deployed within cities, pedestrians may have to become more aware of their surroundings, particularly as children and pets familiarize themselves with the devices.

Dogs reacting viscerally to the PDDs caused an obstruction on the sidewalk and forced other pedestrians to either change their pace or path. Whether the pedestrians notice the PDDs, seeing dogs behaving so actively can be startling and those around may respond by giving the owner and their pet more space. Having the pet, the owner, and other passersby simultaneously reroute and seek additional space on the sidewalk can be hazardous, and pedestrians may end up walking in the street (as we saw in the first scenario). Sidewalks are limited in space and these kinds of reactions from dogs and their owners can introduce potentially dangerous obstacles.

As described earlier, pedestrians with children may become frustrated with PDDs as they prove to be a distraction for children. We observed a similar reaction with pedestrians who have pets, illustrated in Figure 5.

> A woman and her golden retriever puppy walk towards the robot, with the puppy in front of the woman. When they are about 3–4 feet from the robot, the dog begins to slow down and then steps back towards the woman. It shrinks its body between her legs and lowers its head. The woman leans over the dog and says, "It's OK, don't be scared." She walks in front of the dog, and tugs at its leash multiple times before it begins to follow her. She sighs and yanks the leash and the dog begins to move, taking wide, rounded steps to keep distance from the robot. (Observation, 8 December 2021).

(**A**) (**B**)

Figure 5. (**A**) A woman takes a picture of the PDD while her two dogs try to move away, (**B**) a dog stops barking at the device to sniff it out after reassurance from the owner.

As pets become distracted by PDDs, their owners may become frustrated by their lack of obedience. In the above vignette, the dog appears to be frightened, as it refuses to move closer to the PDD. This is in opposition to the presumed goals of the owner, who is attempting to walk said pet. The sudden stop proves to be a moment of annoyance, and that negative feeling may become associated with the PDD.

5.3. Need for Human Assistance

The unpredictability of the urban environment often led to unforeseen events, which we were able to quietly monitor and make note of. Over time, certain patterns began to emerge where PDDs could not be as self-sufficient by relying on their programming or remote operators, and in-person assistance was required. We observed several instances when the robot was unable to move because of an obstacle, such as a pavement crack. When obstacles were encountered, the PDD relied on human intervention to get back on its way. Sometimes, this was conducted by a Kiwibot staff member who was monitoring nearby in the neighborhood and would travel to the robot.

Without communication from the device, pedestrians had to use context clues to know that the PDD was stuck and in need of human assistance. As seen in Figure 6, a man walking his dog uses a stuck robot as an opportunity to take a picture, instead of helping the device. While in close proximity to the device, the man never touches it or shows any indication of attempted assistance.

Figure 6. A man poses his dog in front of a stuck robot.

In other cases, pedestrians would help the robot resume its normal activity. This proved to be both useful for the device and seemingly rewarding for the pedestrian.

> The PDDs front wheel fell into a road verge and became stuck. A woman who was walking in the same direction stopped moving when she was parallel to the device. She slowly approached the device, crouching a bit as she side-stepped to it. When she was inches away, she stopped moving, looked directly down at the device, and put both hands on her hip. Her lips were pursued, and she had one eyebrow raised. She bent down, put her face right next to the PDD, and frowned. She tilted her head to look at the front wheels, then back at the device, then back to the wheels. After a minute, she put both hands on both sides of the PDD and spoke to it softly. She lifted it out of the crack, patted it on the top, and kept walking. As she walked, she teetered side to side and smiled to herself (Observation, 3 November 2021).

Without any communication or information on the system status from the device, the woman assessed the situation and deduced next steps on her own. She took time to evaluate the device, its wheels, and the matter in which it is stuck. In choosing to speak to the device, the rescuers' actions highlight an innate interest in sociability. The woman initiated the conversation, but due to the device's limited communication capabilities, her remarks were not met with a response. However, the woman's body language and facial expression after assisting the device indicated she may have taken some pleasure in assisting the device.

In another incident, a pedestrian recognized that the device was trapped, but, without a call to action, they did not know if they should help or how to do so.

> A vacuum tube was set up from a retail store to a company van, spanning the width of the sidewalk. When the robot was 1 foot away from the tube, it stopped, paused for a moment, turned around, and rolled in the opposite direction. It repeated this sequence, unable to move past the tube. I stood on the street corner, facing away from the device. A woman stood next to me, waiting for the light to change. Her head is turned, facing the device. She looked toward the direction the device had come from and nodded her head to the vacuum tube and said "I think it's stuck. I was shopping there, and I kept seeing it from the window. I don't think it can get through." She looked at me and laughed, and then said, "I bet someone is missing their delivery." (Observation, 5 November 2021).

Through context, the woman understood that the PDD was attempting to make a delivery, but because of the environment, the robot was unable to continue moving. The device had no method for active communication, and, therefore, could not initiate an interaction. Her use of minimizing language suggested her uncertainty about what to do, stemming from a lack of information. Without communication, the device must rely entirely on the curiosity, interest, or goodwill of nearby pedestrians for help.

In the final weeks of the study, the device emitted non-linguistic sounds and displayed written directives on the digital screen as new methods of communication. This seemed to only occur when there was an error or problem with the PDD. While pedestrians were still cautious to interact, they showed a higher interest in helping, as evidenced by an increased engagement with the robot.

> The PDD falls into a grate off the sidewalk, caught between the pavement and the dirt. The device begins to emit a loud siren sound, and the text on the face reads "`HELP ME`." A woman, passing by while talking on her phone, walks directly over to the PDD. She cautiously leans over to read the screen. Speaking into her phone, she says, "It fell on the sidewalk. I think it's a delivery robot." She uses her foot to move the device out of the grate and laughs. When the device was fully on the sidewalk, the screen changed to display, "`THANK YOU.`" She then says into the phone, "Hold on, I have to take a picture of this. It's so sweet." and proceeds to photograph the robot before walking forward. (Observation, 30 November 2021).

In this instance, also shown in Figure 7, the PDD used both sound and text to engage and communicate with passersby. The sound called attention to the device, and the use of a siren communicated that a malfunction had occurred. Using a familiar sound, such as a siren, can express action is needed by the pedestrian. Once the pedestrian moved closer to the device, they were able to see and read the text, which functioned as a call to action. While specific steps on how to help were not given, the directive of 'HELP ME' called on the pedestrian to engage with the device.

Figure 7. A PDD stuck in a grate requires human assistance to regain mobility.

While the sound serves as an alert and an initial tool for awareness, it might not offer enough information to support confident pedestrian action. As in the other moments, the passersby here approached with hesitation, though in this case, her path to the device was more direct. Upon reading the screen, she acted. Where in other moments, the device might be inspected first or ignored entirely, the direct action here may have been a result of the device's communication.

The PDD ended the engagement by displaying the words 'THANK YOU' on its screen and began to move on its route. We saw the user respond positively, verbally acknowledging the affirmation from the device. Such social signaling may help to develop a relationship between itself and the pedestrians.

A sense of accomplishment from a helpful pedestrian is seen again in the incident with the PDD and the vacuum tube. Figure 8 shows another pedestrian acting as a rescuer and having a positive reaction following the experience.

> A PDD is about 5 feet from the tube and a construction worker notices the device approaching. He stops in the middle of the sidewalk to watch the device roll

> toward him. When the PDD is about 1–2 feet from the tube, the man looks down at the tube and then lifts it, allowing the PDD to roll underneath it. As the PDD rolls by, the man's head turns with it, to watch it pass through. His lips turn upwards into a small smile, and he nods to the device after it has fully passed. He puts the tube down and continues to watch the device until it is about 4–5 feet away, and then he turns his attention back to his work. (Observation, 5 November 2021).

Figure 8. A man lifts a tube so the PDD can pass underneath and continue its route.

In this case, the man was able to preemptively assist the PDD before it was unable to move again. While pedestrian assistance should not be necessary for successful delivery, communicating the robots' state with people who may choose to act as rescuers can improve the experience of sharing the sidewalk.

Our research demonstrates that pedestrians are open to directly interacting with devices when they believe support is necessary. Evidence for this is supported by prior work with robotic trash cans where struggling behavior encourages individuals to help the robot [45]. Despite our observations of some people providing assistance, many were hesitant to engage. For example, even when the noted pedestrian saw the words "`HELP ME`" displayed on the front of the robot, she was reluctant to help. Despite the directional message from the robot, the woman still used only the toe of her boot to move it, jumping away after, with an uncertainty to her movements.

5.4. Accessibility Considerations and Issues

In the months-long deployment of PDDs in the City of Pittsburgh, the research team rarely observed testing or interaction with people with disabilities or those utilizing mobility equipment. Although a known issue in past deployments of PDDs manufactured by other companies [17], this did not seem to be a focus of the pilot program. During one instance, we observed a woman in a wheelchair and a PDD enter a crosswalk from opposite ends. As seen in Figure 9, the woman and her caretaker stopped in the middle of their walk to watch the PDD. After the interaction, we spoke with the woman about her experience.

> On her overall sentiment: "I like those little robot things...I think they're cool looking, I like their little face on the front."
> On a scale of 1–5, 1 being 'dangerous' and 5 being 'very safe': "I'd say a 5. They stop if something is in their way, they won't move again until the other thing has moved. Before it even comes in contact, before it even gets to you, it will stop until you move and then it will keep going." (Interview, 17 November 2021).

Figure 9. Two women stop mid-crosswalk to see if the PDD will cross as well.

To this woman, the familiar elements of the robot's "face" bring her both comfort and joy. In other interviews we conducted, pedestrians also had positive sentiments toward the robot's face. In referring to the device as 'they' instead of 'it', the woman personifies the robot. It is possible that the colorful and familiar symbols (such as hearts) in place of and in addition to digital eyes endow the robot with socialness and lead people, who will treat technology socially [46], towards more social engagements with the robot.

The woman was also able to predict the robot's behavior after a brief interaction, aware that the PDD gave the right of way to the pedestrian by stopping in place. The PDD only began to move again when it detected that the person or obstacle had moved as well. She described this practice as safe because she saw it as minimizing the possibility of collision. She recognized a criterion the device used in making decisions—that the PDD was aware of her movements and reacted accordingly, and that understanding influenced her own movement. She also noted the robot played a passive role in the interaction, waiting "until" she made a move. Allowing the pedestrian to move first, without having to determine where the robot might simultaneously move, allowed her to decipher what action would be best in response. The pedestrian was given time to survey the space and plan and execute her movement without feeling rushed by the oncoming PDD.

Despite this encounter, we note that people who use canes, wheelchairs, or other mobility devices and aids, as well as people who are deaf or hard of hearing were not widely seen by our team while observing the pilot. With that being said, the Pittsburgh City-County Task Force on Disabilities was active at the time in voicing concerns about the introduction of micromobility technologies and how they would affect the experience of disabled sidewalk users. This not only applied to PDDs but also to electric scooters widely introduced across cities in the past few years. We attended multiple town hall-style meetings where members of the Task Force implored DOMI representatives to understand that the standard of a one-hour maximum for moving a scooter blocking the sidewalk was not sufficient. If a person using a wheelchair is unable to pass for a full hour due to a scooter blockage, or a PDD in the case of this research, that is harmful, particularly to a pedestrian who has not opted-in to using the PDD or sharing space with it. We would urge future studies and pilot programs to consider these cases since a PDD could disproportionately affect the experience of disabled people using public sidewalks and may introduce accessibility violations (in nations where there are regulations, such as the United States Americans with Disabilities Act).

6. Discussion

Through the team's field observations and interviews, we witnessed various positive and negative interactions that community members had in response to the robots. For some, the robots were a cute addition to public walkways, echoing Dobrosovestnova et al's [26] observations of delivery robots in Estonia. Some residents optimistically viewed the robots as a way to deliver food, medicine, or books. A subset even imagined that in wintry and rainy conditions, the robots could help run errands when people would not want to go outside (notably, the robots we studied were not able to run in snow or rain). For others, such as dog owners, the robots caused issues during what would normally be an uneventful walk. These interactions were similar to those found in [20], where dog owners needed to move away from the robot due to their dogs barking at it. While such conflict between dogs and robots was not hugely problematic, the increased presence of robots could lead to higher rates of confrontation, dogs barking, and dogs lunging towards robots—actions that may turn quiet sidewalks into louder and more stressful scenarios for pedestrians and local neighbors.

Regarding the robots' interactions with the built environment, there were many obstacles they encountered, such as planters and grates (Figure 7) or work equipment (Figure 8), halting their movement and thus, reducing their effectiveness as delivery agents. We observed some passersby chose to help the robots, similar to [26]; particular robot design elements such as dynamic messages written across the screen such as "`Help`" and "Thank You" seemed to encourage this behavior, similar to prior studies on effective robot communication to engender interactions in public [34]. That being said, such helpful behavior is not guaranteed. Many people would pass by the robot without helping, even if they may have understood it to be stuck (Figure 6). While improved communication design through lights and dynamic displays [30,31,39], sounds to engender empathy [28], or movement to signal intent [29,32,33] may improve communications and interaction with some people, it is also possible that some members of the public will not engage with the robots or will be actively antagonistic towards them. Such behaviors are evidenced by the incident reports provided after the pilot. Such blatant ignoring or antagonism of a robot may suggest that people do not view them as part of the community, as described by Lupetti et al. [40]. As they suggest, there may be opportunities within the design space to better position robots within the community fabric. Given what we observed, we make some recommendations for future sidewalk robot pilot programs and consider how robots may be designed to enhance public services and foster positive interactions. We also describe the limitations present in this study and suggest future research that could be done in additional public deployments of sidewalk robots.

6.1. Public Communication about Public PDD Pilots

Across our observations, we witnessed many pedestrians who were surprised or confused to see a PDD in their space, suggesting that residents were unaware of the pilot. Testing different and more accessible resources and information channels would have likely helped to inform a greater majority of pedestrians of pilot tests underway. Furthermore, different methods of communication in the moment may be needed to inform residents of pilot tests and educate them on PDDs. In the absence of communication, residents were left to come up with their own explanations for the devices' presence. This included theories on the goods they might be delivering (e.g., pizza) or who might be behind their use (e.g., the post office). Though largely harmless in the cases we observed, it is not difficult to imagine how folk theories about their use could spur worry and doubt. Pedestrians may wonder if they are being surveilled [16], and such feelings could possibly be part of why some people are antagonistic to the robots. Rather than leaving residents to fill in the blank, cities could instead engage them along the way—from determining pilot projects to evaluating their performance. For example, the choice of the function the robots served in the community could be determined in a public forum (particularly, as the city was interested in public responses to the robots rather than the utility of the devices per se). This could involve more opportunities for education around sidewalk robots, possible models for public pilots, and suggest how PDDs might contribute or distract from efforts to support public good and open and accessible walkways.

6.2. Managing Appropriate Navigation

Across our observations, we did not observe any collisions or near collisions. This is likely due to the low pedestrian density of the routes selected for testing and the stop-and-wait strategy employed by the robot when encountering people too closely, as described by the wheelchair user in Section 5.4. However, prior work have observed near collisions, such as those in a college campus environment [4], and a PDD blocked access to a curb cut during an earlier sidewalk delivery robot pilot in Pittsburgh [17]. Thus, there needs to be continued research on socially appropriate and safe navigation and communication between robots and pedestrians. Future pilots should consider testing in areas with higher pedestrian density. Furthermore, robot designers and cities might leverage simulation of social navigation [22,23] by modeling their local context (i.e., sidewalk sizes, pedestrian density, sidewalk conditions) and simulating possible issue scenarios that could occur.

6.3. Inviting Interaction

Our observations suggest that pedestrians are open to directly interacting with sidewalk robots when they believe the device has created an opportunity for socialization (i.e., through facial expression or text and verbal appeals for help). These findings resonate with prior research on robot communication in public spaces; studies that have suggested that screen interfaces with dynamic information [34] and sounds [28] can both be helpful for engaging people and information about the robot's intent. Future robot designs and deployment planning teams should consider and incorporate recommendations and best practices for communication based on prior work. Furthermore, they may test such displays with the resident population to understand what kinds of communications are more interpretable to the local community. As noted by [29], much prior work on robot communication has found that it was only after a short period of education that people can understand the intent of the robot [30]. Given that most people will likely not have an opportunity to learn about and experience the robot before an encounter in public, it is important to identify and design signals and messages that can be interpreted quickly and accurately.

In the case of this pilot, there were instances where pedestrians appeared to be unsure of how to interact with the PDD, especially when hands-on assistance was needed. At the start of the Pittsburgh pilot, a siren was used when the robot was stuck; however, this could be misinterpreted as a sign to stay away. Instead, clear messages of help written on a screen proved more interpretable and may have been possible to design with community input before the deployment. We believe that testing additional communication modes is needed to inform human-robotic assistance. How can the PDD invite and inform pedestrians of needed aid without being a disturbance to those nearby? Exploration of the use of sounds, digital displays, and possibly even casing design, such as the extendable handle of a 'handleable' robot proposed by Lupetti et al. [40], can offer new and more effective communication. The use of directional, written communication and sound would likely encourage pedestrians to interact with PDDs, and even assist the devices when needed. When pedestrians are given directions and are engaged in maintenance, some may respond positively as we saw with the pedestrian helpers in Section 5.3. However, as discussed in Dobrosovestnova et al. [26], it is important to consider whether a PDD soliciting help, perhaps by acting endangered or in need of assistance, is manipulative to pedestrians passing by. Is it the responsibility of the robotics company or the city to handle these robots when they run into issues? Or will community residents be tasked with robot maintenance and care as part of some shared responsibility within the community [40]?

6.4. Dissuading Interaction

Beyond inviting interaction, we also argue that further research is needed to explore methods for discouraging interaction. As observed, robotic interaction with children and pets often caused obstacles for other pedestrians. Additionally, robots were vandalized, kicked, or picked up and placed off their routes numerous times during the pilot. Prior work has explored evasive maneuvers in more open spaces by developing robot navigation algorithms that have them move away from abusive persons and toward other people whose presence can diffuse the situation [47]. However, such behaviors may not work on narrow sidewalks where there is less space to move, where people may not be close to each other, and where erratic evasive maneuvers could pose challenges to other pedestrians. Future work may consider how PDDs can facilitate interactions that maintain positive interactions or at least dissuade people from interacting more directly, while setting boundaries that keep all pedestrians safe.

6.5. Limitations

The limited size of the pilot led to us only observing in a small area of the wider city of Pittsburgh. Further, during our observations, the streets in the selected neighborhoods were not particularly dense with pedestrians, meaning that we only observed and interviewed a limited number of people. There was also a lack of socioeconomic and racial diversity in the neighborhoods tested. To make general observations about how robots would operate in Pittsburgh as a whole or in other large cities, we recommend broader testing in varied neighborhoods. This would include the study of cultural and material differences.

While there has been much evidence of delivery robots and other sidewalk technologies, such as scooters, causing problems for accessibility, we did not conduct direct research with disabled people to study these possible issues. To make clear and scientifically backed policy recommendations and conclusions on the ways PDDs should navigate the sidewalk and communicate with people, we believe there needs to be participatory research and design conducted with people with disabilities. We recommend pilots widen their scope of testing and increase engagement with disability advocacy groups to ensure PDD standards are inclusive. Further research is needed to define these signals, such as the type of audio cues (voice vs. non-linguistic sound) or visual cues. Defining how and when these signals are used increases the chance of their success. Variations of these signals need to be tested to design inclusive devices that can engage all pedestrians.

7. Conclusions

This observational research aimed to explore pedestrians' interactions with and perceptions of delivery robots, specifically in the unpredictable realm of public sidewalks. We observed interactions that were initiated by both the robot and pedestrians, the latter of which included but was not limited to adults, children, and pets. Many of the observed interactions involved people's curiosity towards the robot, in which they approached the robot to learn more or engaged with other pedestrians to share theories on the device's purpose. We also observed people's helpful behavior toward robots that were immobilized and learned about reported incidents of vandalism where people actively antagonized the robot. In both cases, the intentional design of the robot and its many interfaces, along with outreach and education about these new devices may help to improve interactions between pedestrians and the robots.

Author Contributions: S.E.F. and N.M. conceived and planned the research protocol. Data collection was completed by D.W. and H.D. Data were organized and analyzed by D.W. and H.D. Supervision and project administration of project activities were conducted by S.E.F. and N.M. All authors contributed to the initial and final draft of the manuscript, as well as the review and editing of the manuscript. All authors have read and agreed to the published version of this manuscript.

Funding: This material is based upon work supported by the National Science Foundation under Grant No. 2125350 *SCC-PG: Equitable new mobility: Community-driven mechanisms for designing and evaluating personal delivery device deployments*.

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki, and approved by the Institutional Review Board of Carnegie Mellon University (STUDY2021 00000239 approved 16 July 2021 & STUDY2021 00000271 approved 1 November 2021).

Informed Consent Statement: Consent for observation of participants was waived due to observations occurring in public and the need to remain unnoticed by people and observe their natural interaction with the robot. Informed consent was obtained from all interview subjects involved in the study.

Data Availability Statement: Data from the study made available upon request.

Acknowledgments: The authors would like to thank the City of Pittsburgh's Department of Mobility and Infrastructure (DOMI) and Kiwibot for granting us permission to observe the robot delivery pilot. In particular, we thank Erin Clark and Chase Klingensmith for their engagement with our research, and for preparing and sharing the DOMI final report on the delivery robot pilot. We thank the Bloomfield Development Corporation and the residents of Pittsburgh for allowing us to attend community meetings about the delivery robot pilot. Finally, we thank our interview participants for their participation in our research.

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

PDD	Personal delivery device
DOMI	Department of Mobility and Infrastructure

Appendix A. Field Observations Guide

The following was the field observation guide that was used to direct the observer's attention and prompt their notetaking.

Research Question: What do people's interactions look like with the robots over the course of the pilot deployment?

1. Interaction dynamics of the robots as they navigate and as they interact with people.
    - How is the robot moving?
    - How is the robot performing?
    - Is the robot able to move around people that step in its way?
    - Does the robot navigate obstacles on the sidewalk (i.e., light poles, bikes, or scooters)?
2. Note down the following movement attributes:
    - Speed
    - Direction
    - Location on sidewalk
    - Stops and starts
    - Obstacles encountered
3. If a Kiwibot staff member comes up to the robot:
    - What does the staff member appear to do with the robot?
    - How long is the staff member there with the robot?
4. When the robot interacts with someone:
    - Does the robot move around them?
    - Does the robot stop for them and give them the right of way?
    - Does the robot not move out of the way and the person needs to change their path?
    - Does the robot signal to them in any way?
5. When a person approaches the robot, do they:
    - Change their direction or location on the sidewalk?
    - Stop and give the right of way to the robot?
    - Try to interact with the robot through voice, gesture, or movement?
    - Test/mess with the robot in any way?
    - Actively vandalize or harm the robot?
6. Information on people interacting with robot:
    - Age appearance [child, young adult, middle age, elderly]
    - Use of assistive device? [cane, walker, crutches, powered wheelchair, manual wheelchair, mobility scooter, etc.]
7. Try watching for any interaction with the robots by bystanders, not in the direct path of the robot.
    - Do people stare at the robot for an extended time?
    - Do people seem to not acknowledge the robot or do they not seem to notice?

Appendix B. Intercept Interview Questions

Intercept interview questions (All questions are optional, you may skip any)

- Age (open-ended response, prefer not to answer)
- Gender (open-ended response, prefer not to answer)
- Education (primary school, high school, college, postgraduate school, prefer not to answer)
- Income (You can tell us a range (Under 50 K, 50–100 K, 100–150 K, 150–200 K, etc), prefer not to answer)
- Race/Ethnicity (open-ended, prefer not to answer)
- Employment (Yes/no and what industry, or retired—open-ended, prefer not to answer)

On a scale of 1 to 5. What is your overall impression of sidewalk delivery robots?
1 (I hate them) 2 3 4 5 (I love them)

Sidewalk robots are competent
1 (strongly disagree) 2 3 4 5 (strongly agree)

Sidewalk robots are dangerous
1 (strongly disagree) 2 3 4 5 (strongly agree)

Sidewalk robots are sociable
1 (strongly disagree) 2 3 4 5 (strongly agree)

Sidewalk robots are responsive
1 (strongly disagree) 2 3 4 5 (strongly agree)

Sidewalk robots are aggressive
1 (strongly disagree 2 3 4 5 (strongly agree)

Sidewalk robots are important to me
1 (strongly disagree) 2 3 4 5 (strongly agree)

Sidewalk robots are important for society
1 (strongly disagree) 2 3 4 5 (strongly agree)

Sidewalk robots are trustworthy
1 (strongly disagree) 2 3 4 5 (strongly agree)

Open ended questions:

Thank you, now we would like to ask you some open-ended questions. We ask that you not reveal any private or personally identifiable information about yourself OR others in your responses to the open-ended questions.
If a sidewalk robot has just gone by:

- Can you describe what it was like to go by the sidewalk robot?
- Did you feel like the robot affected your movement on the sidewalk?
- Can you describe how you felt the robot navigated the sidewalk?

Otherwise:

- Have you ever seen a sidewalk robot?
- Can you describe what it was like to go by the sidewalk robot?
- Can you describe how you felt it navigated the sidewalk?
- Do you think sidewalk robots are safe? Why or why not?
- Did you feel obstructed by the sidewalk robot?

- Have you heard much about sidewalk robots? If so, what sources did you learn information from?
- Have you heard about this deployment of Kiwibots in Bloomfield?
- Do you have any concerns about the sidewalk robots?
- Have you encountered a sidewalk robot at a street crossing? As a pedestrian, as a cyclist, or as a driver?
- If a sidewalk robot has a problem, how could it let a pedestrian, cyclist, or driver know a problem is occurring? (After they answer, also suggest: Lights? Sounds?Wireless messages to your phone, etc?)
- Do you have any ideas for things that would make the sidewalk robot better for you as a pedestrian?
- Do you have any other ideas about how these sidewalk robots could be used?
- Would you consider receiving a delivery from a sidewalk robot?
- What do you know about how a sidewalk robot works?
- Is there anything else you would like to tell us?

References

1. Hossain, M. Self-Driving Robots: A Revolution in the Local Delivery. California Management Review. 2022. Available online: https://cmr.berkeley.edu/assets/documents/pdf/2022-04-self-driving-robots-a-revolution-in-the-local-delivery.pdf (accessed on 13 May 2023).
2. Hoffmann, T.; Prause, G. On the regulatory framework for last-mile delivery robots. *Machines* **2018**, *6*, 33. [CrossRef]
3. McQueen, M.; Abou-Zeid, G.; MacArthur, J.; Clifton, K. Transportation transformation: Is micromobility making a macro impact on sustainability? *J. Plan. Lit.* **2021**, *36*, 46–61. [CrossRef]
4. Gehrke, S.; Phair, C.; Russo, B.; Smaglik, E. Observed sidewalk autonomous delivery robot interactions with pedestrians and bicyclists. *Transp. Res. Interdiscip. Perspect.* **2023**, *100789*, 1–11. [CrossRef]
5. Pani, A.; Mishra, S.; Golias, M.; Figliozzi, M. Evaluating public acceptance of autonomous delivery robots during COVID-19 pandemic. *Transp. Res. Part D Transp. Environ.* **2020**, *89*, 102600. [CrossRef]
6. City of Pittsburgh. City Partners with Kiwibot to Pilot Free Delivery of Food, Medicine and Books by Delivery Robot. 2021. Available online: https://pittsburghpa.gov/press-releases/press-releases/5294 (accessed on 13 May 2023).
7. Nardi, B.A. The use of ethnographic methods in design and evaluation. In *Handbook of Human-Computer Interaction*; Elsevier Science: Amsterdam, The Netherlands, 1997; pp. 361–366.
8. Dourish, P. Reading and interpreting ethnography. In *Ways of Knowing in HCI*; Springer: New York, NY, USA, 2014; pp. 1–23.
9. Marks, M. Robots in space: Sharing our world with autonomous delivery vehicles. *SSRN Electron. J.* **2019**. Available online: https://ssrn.com/abstract=3347466 (accessed on 13 May 2023). [CrossRef]
10. Deng, P.; Amirjamshidi, G.; Roorda, M. A vehicle routing problem with movement synchronization of drones, sidewalk robots, or foot-walkers. *Transp. Res. Procedia* **2020**, *46*, 29–36. [CrossRef]
11. Schröder, J.; Heid, B.; Neuhaus, F.; Kässer, M.; Klink, C.; Tatomir, S. *Fast Forwarding Last-Mile Delivery: Implications for the Ecosystem*; McKinsey: New York, NY, USA, 2018.
12. Jennings, D.; Figliozzi, M. Study of sidewalk autonomous delivery robots and their potential impacts on freight efficiency and travel. *Transp. Res. Rec.* **2019**, *2673*, 317–326. [CrossRef]
13. Rai, H.B.; Touami, S.; Dablanc, L. Autonomous e-commerce delivery in ordinary and exceptional circumstances. The French case. *Res. Transp. Bus. Manag.* **2022**, *45*, 100774.
14. Wong, J.C. Delivery robots: A revolutionary step or sidewalk-clogging nightmare? *The Guardian*, 12 April 2017.
15. Salvini, P.; Paez-Granados, D.; Billard, A. On the Safety of Mobile Robots Serving in Public Spaces: Identifying Gaps in EN ISO 13482:2014 and Calling for a New Standard. *J. Hum.-Robot Interact.* **2021**, *10*, 1–27. [CrossRef]
16. Thomasen, K. Robots, Regulation, and the changing nature of public space. *Ott. Law Rev.* **2020**, *51*. Available online: https://ssrn.com/abstract=3589896 (accessed on 13 May 2023).
17. Bennett, C.; Ackerman, E.; Fan, B.; Bigham, J.; Carrington, P.; Fox, S. Accessibility and The Crowded Sidewalk: Micromobility's Impact on Public Space. In Proceedings of the Designing Interactive Systems Conference 2021, Virtual, 28 June–2 July 2021; pp. 365–380.
18. Abrams, A.; Platte, L.; Rosenthal-von der Putten, A. Field observation: Interactions between pedestrians and a delivery robot. In Proceedings of the IEEE International Conference on Robot & Human Interactive Communication (ROMAN'20), Virtual, 31 August–4 September 2020.
19. Vroon, J.; Rusák, Z.; Kortuem, G. Context-confrontation: Elicitation and exploration of conflicts for delivery robots on sidewalks. In Proceedings of the First International Workshop on Designerly HRI Knowledge: Held in Conjunction with the 29th IEEE International Conference on Robot and Human Interactive Communication (RO-MAN 2020), Virtual, 31 August–4 September 2020.

20. Van Mierlo, S. Field Observations of Reactions of Incidentally Copresent Pedestrians to a Seemingly Autonomous Sidewalk Delivery Vehicle: An Exploratory Study. 2021. Available online: https://mwlc.global/wp-content/uploads/2021/08/Thesis_Shianne_van_Mierlo_6206557.pdf (accessed on 13 May 2023).
21. Kruse, T.; Pandey, A.K.; Alami, R.; Kirsch, A. Human-aware robot navigation: A survey. *Robot. Auton. Syst.* **2013**, *61*, 1726–1743. [CrossRef]
22. Biswas, A.; Wang, A.; Silvera, G.; Steinfeld, A.; Admoni, H. SocNavBench: A Grounded Simulation Testing Framework for Evaluating Social Navigation. *J. Hum.-Robot Interact.* **2022**, *11*, 1–24. [CrossRef]
23. Karnan, H.; Nair, A.; Xiao, X.; Warnell, G.; Pirk, S.; Toshev, A.; Hart, J.; Biswas, J.; Stone, P. Socially compliant navigation dataset (scand): A large-scale dataset of demonstrations for social navigation. *IEEE Robot. Autom. Lett.* **2022**, *7*, 11807–11814. [CrossRef]
24. Mavrogiannis, C.; Alves-Oliveira, P.; Thomason, W.; Knepper, R.A. Social Momentum: Design and Evaluation of a Framework for Socially Competent Robot Navigation. *J. Hum.-Robot Interact.* **2022**, *11*, 1–37. [CrossRef]
25. Vroon, J.; Zhou, Y.; Rusak, Z. Detecting Emerging Challenges in Social Sidewalk Navigation. In Proceedings of the Urban AI: Formulating an Agenda for the Interdisciplinary Research of Artificial Intelligence in Cities, Eindhoven, The Netherlands, 8 June 2020.
26. Dobrosovestnova, A.; Schwaninger, I.; Weiss, A. With a Little Help of Humans. An Exploratory Study of Delivery Robots Stuck in Snow. In Proceedings of the 2022 31st IEEE International Conference on Robot and Human Interactive Communication (RO-MAN), Napoli, Italy, 29 August–2 September 2022; pp. 1023–1029.
27. Backhaus, N.; Rosen, P.H.; Scheidig, A.; Gross, H.M.; Wischniewski, S. "Somebody help me, please?!" interaction design framework for needy mobile service robots. In Proceedings of the 2018 IEEE workshop on advanced robotics and its social impacts (ARSO), Genova, Italy, 27–29 September 2018; pp. 54–61.
28. Holm, D.G.; Junge, R.P.; Østergaard, M.; Bodenhagen, L.; Palinko, O. What Will It Take to Help a Stuck Robot? Exploring Signaling Methods for a Mobile Robot. In Proceedings of the 2022 17th ACM/IEEE International Conference on Human-Robot Interaction (HRI), Sapporo, Japan, 7–10 March 2022; pp. 797–801.
29. Angelopoulos, G.; Rossi, A.; Di Napoli, C.; Rossi, S. You Are In My Way: Non-verbal Social Cues for Legible Robot Navigation Behaviors. In Proceedings of the 2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Kyoto, Japan, 23–27 October 2022; pp. 657–662.
30. Fernandez, R.; John, N.; Kirmani, S.; Hart, J.; Sinapov, J.; Stone, P. Passive demonstrations of light-based robot signals for improved human interpretability. In Proceedings of the 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), Nanjing, China, 27–31 August 2018; pp. 234–239.
31. Hart, J.; Mirsky, R.; Xiao, X.; Tejeda, S.; Mahajan, B.; Goo, J.; Baldauf, K.; Owen, S.; Stone, P. Using human-inspired signals to disambiguate navigational intentions. In Proceedings of the Social Robotics: 12th International Conference, ICSR 2020, Golden, CO, USA, 14–18 November 2020; Springer: Cham, Switzerland, 2020; pp. 320–331.
32. Reinhardt, J.; Prasch, L.; Bengler, K. Back-off: Evaluation of robot motion strategies to facilitate human-robot spatial interaction. *ACM Trans. Hum.-Robot Interact.* **2021**, *10*, 1–25. [CrossRef]
33. Senft, E.; Satake, S.; Kanda, T. Would you mind me if i pass by you? socially-appropriate behaviour for an omni-based social robot in narrow environment. In Proceedings of the 2020 ACM/IEEE International Conference on Human-Robot Interaction, Cambridge, UK, 23–26 March 2020; pp. 539–547.
34. Kannan, S.S.; Lee, A.; Min, B.C. External human-machine interface on delivery robots: Expression of navigation intent of the robot. In Proceedings of the 2021 30th IEEE International Conference on Robot & Human Interactive Communication (RO-MAN), Vancouver, BC, Canada, 8–12 August 2021; pp. 1305–1312.
35. Shrestha, M.C.; Kobayashi, A.; Onishi, T.; Uno, E.; Yanagawa, H.; Yokoyama, Y.; Kamezaki, M.; Schmitz, A.; Sugano, S. Intent communication in navigation through the use of light and screen indicators. In Proceedings of the 2016 11th ACM/IEEE International Conference on Human-Robot Interaction (HRI), Christchurch, New Zealand, 7–10 March 2016; pp. 523–524.
36. Shrestha, M.C.; Onishi, T.; Kobayashi, A.; Kamezaki, M.; Sugano, S. Communicating directional intent in robot navigation using projection indicators. In Proceedings of the 2018 27th IEEE International Symposium on Robot and Human Interactive Communication (RO-MAN), Nanjing, China, 27–31 August 2018; pp. 746–751.
37. Matsumaru, T.; Kusada, T.; Iwase, K. Mobile robot with preliminary-announcement function of forthcoming motion using light-ray. In Proceedings of the 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems, Beijing, China, 9–13 October 2006; pp. 1516–1523.
38. Coovert, M.D.; Lee, T.; Shindev, I.; Sun, Y. Spatial augmented reality as a method for a mobile robot to communicate intended movement. *Comput. Hum. Behav.* **2014**, *34*, 241–248. [CrossRef]
39. Hetherington, N.J.; Croft, E.A.; Van der Loos, H.M. Hey robot, which way are you going? nonverbal motion legibility cues for human-robot spatial interaction. *IEEE Robot. Autom. Lett.* **2021**, *6*, 5010–5015. [CrossRef]
40. Lupetti, M.L.; Bendor, R.; Giaccardi, E. Robot citizenship: A design perspective. In Proceedings of the Design and Semantics of Form and Movement: Desform 2019, Cambridge, MA, USA, 9 October 2019; pp. 87–95.
41. Emerson, R.M.; Fretz, R.I.; Shaw, L.L. *Writing Ethnographic Fieldnotes*; University of Chicago Press: Chicago, IL, USA, 2011.
42. Reig, S.; Norman, S.; Morales, C.G.; Das, S.; Steinfeld, A.; Forlizzi, J. A field study of pedestrians and autonomous vehicles. In Proceedings of the 10th International Conference on Automotive User Interfaces and Interactive Vehicular Applications, Toronto, ON, Canada, 23–25 September 2018; pp. 198–209.

43. Weick, K. *Sensemaking in Organizations*; Sage: Thousand Oaks, CA, USA, 1995.
44. Siino, R.; Hinds, P. Robots, Gender & Sensemaking: Sex Segregation's Impact On Workers Making Sense Of a Mobile Autonomous Robot. In Proceedings of the 2005 IEEE International Conference On Robotics And Automation, Barcelona, Spain, 18–22 April 2005; pp. 2773–2778.
45. Yang, S.; Mok, B.; Sirkin, D.; Ive, H.; Maheshwari, R.; Fischer, K.; Ju, W. Experiences developing socially acceptable interactions for a robotic trash barrel. In Proceedings of the 2015 24th IEEE International Symposium on Robot And Human Interactive Communication (RO-MAN), Kobe, Japan, 31 August–4 September 2015; pp. 277–284.
46. Reeves, B.; Nass, C. The media equation: How people treat computers, television, and new media like real people. *Cambridge UK* 1996, *10*, 236605.
47. Bršćić, D.; Kidokoro, H.; Suehiro, Y.; Kanda, T. Escaping from Children's Abuse of Social Robots. In Proceedings of the Tenth Annual ACM/IEEE International Conference on Human-Robot Interaction, Portland, OR, USA, 2–5 March 2005; Association for Computing Machinery: New York, NY, USA, 2015; HRI '15; pp. 59–66. [CrossRef]