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Observed sidewalk autonomous delivery robot interactions with pedestrians and bicyclists

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A R T I C L E I N F O

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A B S T R A C T

The recent deployment of sidewalk autonomous delivery robots (SADRs) across university campuses has offered students, staff, and faculty a convenient option for food delivery to their residences or workplaces. However, these low-speed automated food delivery services, which were first commercially deployed on American campuses in early 2019 and continued to offer an important contactless delivery service during the height of the Covid-19 pandemic, traverse campuses on pathways originally designed for pedestrians and bicyclists, creating a potential for conflicts among the different pathway users and potentially unsafe transportation conditions. This study examines one week of field-recorded video from ten locations across the Northern Arizona University campus to help understand the prevalence and severity of SADR-involved interactions with pedestrians and bicyclists. The severity of SADR-involved interactions was quantified by using the surrogate safety measure of post-encroachment time, which was then modeled as a function of conflict- and site-level characteristics to identify predictors of moderate or dangerous conflicts between SADRs and human pathway users. Findings from this study, which provides initial real-world insights into the impacts of SADRs sharing pathways with pedestrians and bicyclists, are intended to help inform facility management strategies capable of supporting the safe introduction of this emerging autonomous freight technology on shared-use facilities in current and potential future settings.

Introduction

In 2019, Starship Technologies first launched a commercial fleet of autonomous food delivery services on American college campuses (Starship 2022). Northern Arizona University (NAU) was the second campus to welcome the operation of this new freight delivery technology—a fleet of 30 six-wheeled ground robots outfitted with cameras, ultrasonic sensors, radar, neural networks, and artificial intelligence capabilities that permit a mapping of its physical context and the application of an advanced object-detection system (‘situational awareness bubble’) to sense obstacles such as pedestrians, bicyclists, and other robots along their path (Northern Arizona University (NAU) (2019)). These sidewalk autonomous delivery robots (SADRs) have a travel speed of four miles per hour, weight of 80 lb, and braking distance of one foot (Bogue, 2017; Starship. FAQs, 2023). The ability of SADRs to deliver food orders to NAU students, faculty, and staff via a mobile device app has signified recent advancements in information and communication technologies (Fig. 1). Public health concerns brought by the onset of the Covid-19 pandemic one year after the introduction of SADRs to NAU’s campus further amplified the demand for contactless delivery systems such as Starship’s low-speed automated delivery vehicles, whose service expanded from 500,000 deliveries worldwide at the start of the 2020 academic year to 3,000,000 deliveries by February 2022 (Starship 2022). While increased SADR fleet sizes and service area expansions helped to meet this growing demand for more frequent online food deliveries, the heightened presence of these autonomous devices on pathways shared by pedestrians and bicyclists seeking safe routes for healthy, active travel has also meant greater opportunity for unwelcomed conflict and further obstructions along ever-popular curbside spaces. Yet, the deployment of SADRs based on safety data and an agreed level of risk for human pathway users, who depending on their physiology may incur a set of serious injuries in the event of a collision, has received less regulatory attention than other publicly-available self-driving vehicles (Paez-Granados & Billard 2022).

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Given the growing appeal of SADRs to consumers and marketplaces as well as the current paucity of city or state codes to regulate the safety feature requirements (e.g., braking systems, lights, size and weight limits) and operation (e.g., pedestrian yielding) of SADRs in public spaces (Jennings & Figliozzi 2019), empirical evidence is needed to understand the local context and traffic conditions associated with SADR-involved interactions with human pathway users such as pedestrians and bicyclists. As sidewalk standards evolve and new curb management strategies arise, the management of transportation facilities designed primarily for pedestrians and bicyclists must account for the possibility that low-speed automated delivery services will vie for these public spaces along with emergent micromobility services for passenger travel. Accordingly, an immediate need exists for real-world research exploring the interactions between SADRs and human pathway users that can offer transportation officials and policymakers early insights into the types of conflicts initiated by the introduction of new last-mile food and parcel delivery technologies and the physical settings most likely to create heightened conflict severities and unsafe active travel conditions.

Recognizing the need for empirical research on real-world SADR operations, the objectives of this study are twofold. First, this study aims to generate new evidence regarding the traffic safety experienced by active travelers who share pathways with these recently deployed autonomous food delivery services. This study objective was attained by collecting field-recordings of SADRs operating in mixed traffic settings and adapting a surrogate safety measure (SSM) to define severity of any observed SADR-involved incident. The spatial description of these incidents across ten sites on NAU's main campus in Flagstaff, Arizona and the statistical modeling of SADR-human pathway user conflict severity as a function of conflict- and site-level characteristics will help to address the second study objective, which is to inform future mitigation and facility management strategies that can guide the safe operation of SADRs in new multimodal settings.

Literature review

Empirical studies of traffic safety are often limited by the relative rare nature and randomness of crashes as well as potential inconsistencies related to incident reporting. These conditions and a desire to identify serious interactions that may not result in an observed crash have supported the adoption of SSMs as a useful alternative in the identification and analysis of traffic safety issues, especially those which concern vulnerable road users such as pedestrians and bicyclists (Johnsson et al., 2018). Post-encroachment time (PET) is one such SSM that permits an evaluation of the severity of a traffic incident based on the immediacy in which a crash was avoided (Allen et al., 1978). Previous research has defined PET as the time elapsed from the moment when a vehicle departs a potential collision site to the moment of arrival at the potential collision site by the conflicting vehicle (Lord, 1996). While early applications of PET centered on the study of motor vehicle traffic safety, more recent research has evaluated the usefulness of this SSM in shared-use, multimodal settings primarily occupied by pedestrians and bicyclists, including a four-day analysis of pedestrian-bicyclist interactions in a shared space on the campus of McGill University (Beitel et al., 2018) and a 12-hour analysis of interactions amongst pedestrians and bicyclists (traditional and electric) in Shenzhen, China (Liang et al. 2021). These past studies and others support the validity of using PET as a SSM for analyzing the physical conditions and user characteristics associated with active traveler safety in shared-use settings. However, to the best knowledge of this study's authors, no research to-date has explored the safety impacts faced by pedestrians or bicyclists in relation to the recent introduction of autonomous delivery robot technologies in public, shared-use environments.

Past studies have adopted PET as a SSM to assess vehicle-pedestrian conflicts. Chen et al. (2019) assessed pedestrian safety conditions associated with right-turning vehicles at two intersections in Beijing, China by collecting two hours of unmanned aerial vehicle video footage. The results from their analysis of 2473 pedestrians and 2897 right-turning vehicles demonstrated that PET was able to accurately assess pedestrian-vehicle conflicts at crosswalks and that danger increased for pedestrians when the right-turning angle of the vehicle increased (Chen et al., 2019). In a second study, Ni et al. (2016) evaluated video collected at three intersections in Shanghai, China that encompassed a total of 1144 vehicle-pedestrian interactions. For this second study, the authors considered interactions with a PET value of less than three seconds as a conflict or critical event, with these more severe vehicle-pedestrian interactions conveying clear site-level spatial patterns (Ni et al., 2016). A third study, which evaluated video data of over 28,000 vehicle-pedestrian interactions at four unsignalized intersections in Poland across two months, highlighted PET as a promising indicator of pedestrian safety in settings without traffic controls (Olszewski et al. 2020).

Other studies have adopted PET as an appropriate SSM for better understanding the patterns and predictors of interactions between motor vehicles and bicyclists. Stipancic et al. (2016) evaluated 1514 bicyclist-vehicle interactions extracted from passive video collected at seven intersections in Montreal, Canada, with PET adopted as a SSM suited for vulnerable road user safety. The results from this study, which categorized observed incidents as normal interactions, conflicts, and dangerous conflicts based on calculated PET values, found that bicycle and vehicle speed along with select attributes of the pathway user were significant predictors of increased conflict severity (Stipancic et al. 2016). Another Montreal-based study (Zangenehpour et al. 2016), which collected 90 h of video from 23 intersections in the Canadian city to evaluate the effectiveness of bike lanes in protecting bicyclists from

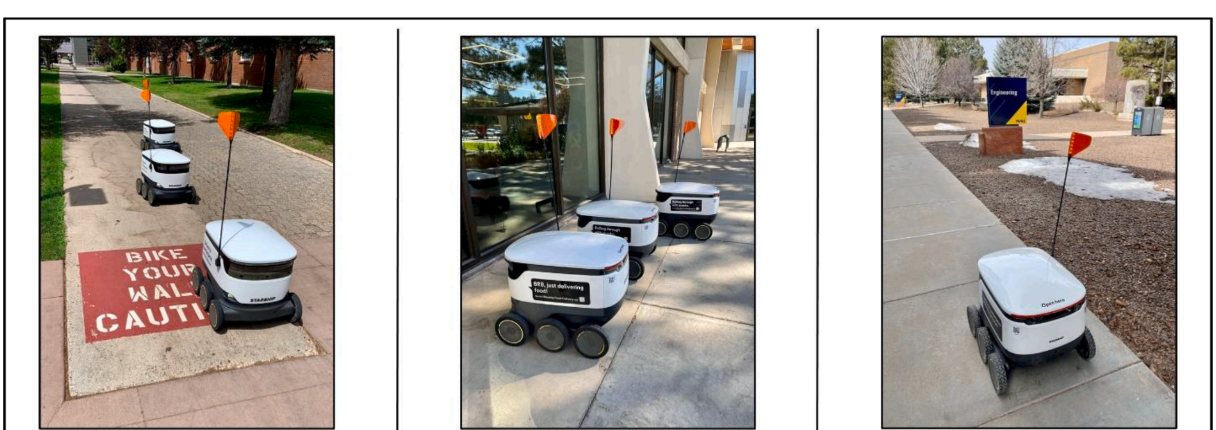

Fig. 1. Sidewalk autonomous delivery robots operated by Starship Technologies on NAU's campus.

turning vehicles, also classified interactions based on PET into three severity levels: very dangerous interactions (PET ≤ 1.5 s), dangerous interactions (1.5 s < PET ≤ 3 s), mild interactions (3 s < PET ≤ 5 s) and no interaction (PET >5 s). The study's estimation of ordered logistic regression models specifying site-level characteristics including bicyclist exposure and bike lane conditions found that higher PET values (i.e., safer traffic conditions) were observed when bike lanes were located on the left side of vehicular traffic rather than the opposing side (Zangenehpour et al. 2016). The adoption of PET and other SSMs has been mutually operationalized in other traffic safety research including a study of 23 h of video from a major intersection in Kunming, China that examined vehicle-involved interactions with powered two-wheelers including e-scooters and e-bikes (Guo et al., 2018). The authors suggest that present applications of PET or other time-proximity safety indicators that utilize fixed geographies for conflict measurement may be limited where mixed road users are likely to share smaller spaces and take evasive actions to avoid a collision (Guo et al., 2018).

As mentioned above, a handful of recent studies have sought to evaluate the safety of pedestrians and bicyclists in smaller shared-use settings. The Beitel et al. (2018) study on McGill University's campus extracted 2739 pedestrian-bicyclist interactions from passively collected video and applied several SSMs including a semi-automated adaptation of the traditional vehicle-involved PET metric based on pedestrian trajectories. However, the authors noted their effort to adapt PET measurements to smaller shared spaces may not be sufficient alone for determining the conflict severity in shared spaces. Nikiforiadis et al. (2020) similarly put forth a new methodology for assessing pedestrian-bicyclist conflicts in shared spaces known as the hindrance concept, which involves the definition of an approximate one-meter radius around the two active travelers involved in the observed interaction. Meanwhile, the aforementioned study by Liang et al. (2021) of active travelers in Shenzhen, used the Dutch Objective Conflict Technique for Operation and Research (DOCTOR) method to define and evaluate vulnerable road user conflicts. From this review, it is evident that the assessment of pedestrian and bicyclist traffic safety conditions in shared-use settings has been explored in a few studies but that (1) limitations persist regarding the translation of PET from an SSM used in vehicle-based studies to a traffic safety indicator in multimodal settings where users are not necessarily confined to a fixed travel lane and (2) previous research on vulnerable road user safety has yet to explore the implications of SADRs or other low-speed automated vehicles entering public spaces that have thus far largely been occupied by human travelers.

Methods

Post-encroachment time (PET) measurement

The SSM of PET was adopted in this study to identify and quantify interactions between SADRs and human pathway users (e.g., pedestrians, bicyclists). PET as opposed to time to collision or other trajectory-related SSMs was chosen due to the manual data collection process of this study, which did not employ computer visioning techniques to help determine travel speeds and path trajectories. To measure the PET associated with an observed interaction, the research team analyzed field-collected video with timestamps from a set of data collection points. The first step toward identifying interactions and measuring their associated PET was to generate a 'bounding box' for each video collection site. The spatial definitions of site-specific bounding boxes were determined by the research team, using physical landmarks that would be visible to a video reviewer who would need to determine if the trajectories of an SADR and human pathway user crossed within the defined boundary. The bounding boxes created for this study had an average area of 1943 square feet (ranging from 503 to 3,550 square feet), with size variations attributed to the angle and height of the stationary video recording devices at each site and site-level decisions regarding the inclusion or exclusion of intersecting pathways.

Interactions between SADRs and human pathway users were later observed within each bounding box, with an associated PET measurement given to identified SADR-related interactions. The PET measure was determined through a multi-step process in which research team members first identified a 'conflict zone' within each video collection site's predetermined bounding box. For this study, a conflict zone was determined to be an area where the observed trajectories of an SADR and human pathway user crossed one another within approximately five seconds. Once an incident-specific conflict zone was identified, the timestamps of when the first pathway user departed the conflict zone ($time_1$) and when the second user arrived to the conflict zone ($time_2$) were recorded, with the PET of the given interaction then calculated as the difference between the two recorded timestamps ($PET = time_2 - time_1$). Fig. 2 provides a visual overview of this sequence for two different conflict types involving an SADR and a pedestrian represented by footprints. When viewing recorded interactions, research team members were able to pause, rewind, and fast forward videos, allowing for greater precision in interaction identification and PET measurement.

Video collection and review

The observation of SADR interactions with human pathway users and associated measurement of PET was conducted after the collection and review of video recorded on NAU's main campus. Video collection was undertaken after identifying study area sites where a reasonable number of interactions between SADRs and other pathway users could be anticipated. After consultation with NAU facility management staff, the research team selected ten sites along highly trafficked pathways in locations near significant SADR origins and destinations (e.g., student unions, residential halls). As shown in Fig. 3, six of the study sites were located on the northern part of NAU's campus, while four were located on the southern portion of campus in proximity to a popular shared-use path leading to the south campus student union. At each of the ten data collection sites, passive video was recorded using high-definition video cameras affixed to extended telescoping poles that were fastened to stationary signs or utility poles adjacent to the bounding boxes. The video cameras were positioned approximately ten feet above the ground, which permitted relatively inconspicuous observations of the natural interactions between SADRs and human pathway users. Videos were recorded from 9am to 6 pm at each site over five days in late September/early October 2021, under clear weather conditions and while in-person classes were held. To streamline data reduction efforts, video review was only conducted during three time periods that coincided with approximate mealtimes when SADRs would be in transit and class transition times where students would also be traveling on the shared pathways: 9:00–10:30am, 11:00am-2:00 pm, and 4:30–6:00 pm. After applying this data reduction step and accounting for periods where continuous video collection was interrupted (i.e., loss in external battery charge), a total of 187 h of passive video across the sites was available for review and analysis.

After the final study observation period was determined, all field-collected recordings, which were parsed into 15-minute video clips, were reviewed by research team members in multiple phases. In the first phase of video review, each site was assigned to a research team member who manually recorded the volumes of SADRs, pedestrians, bicyclists, and other pathway users in each 15-minute video that traveled across one predetermined edge of each study site's bounding box. For the second video review phase, any 15-minute video with one or more observed SADR in the volume count was reviewed by two research team members to identify SADR interactions with human pathway users and record the timestamps associated with each pathway user exiting or entering the conflict zone. Here, research team members applied the PET methodology described in the previous section for all SADR-involved interactions that were judged to have produced a PET value of five seconds or less. Following the second video review phase, the research team members who reviewed videos collected for a given site jointly

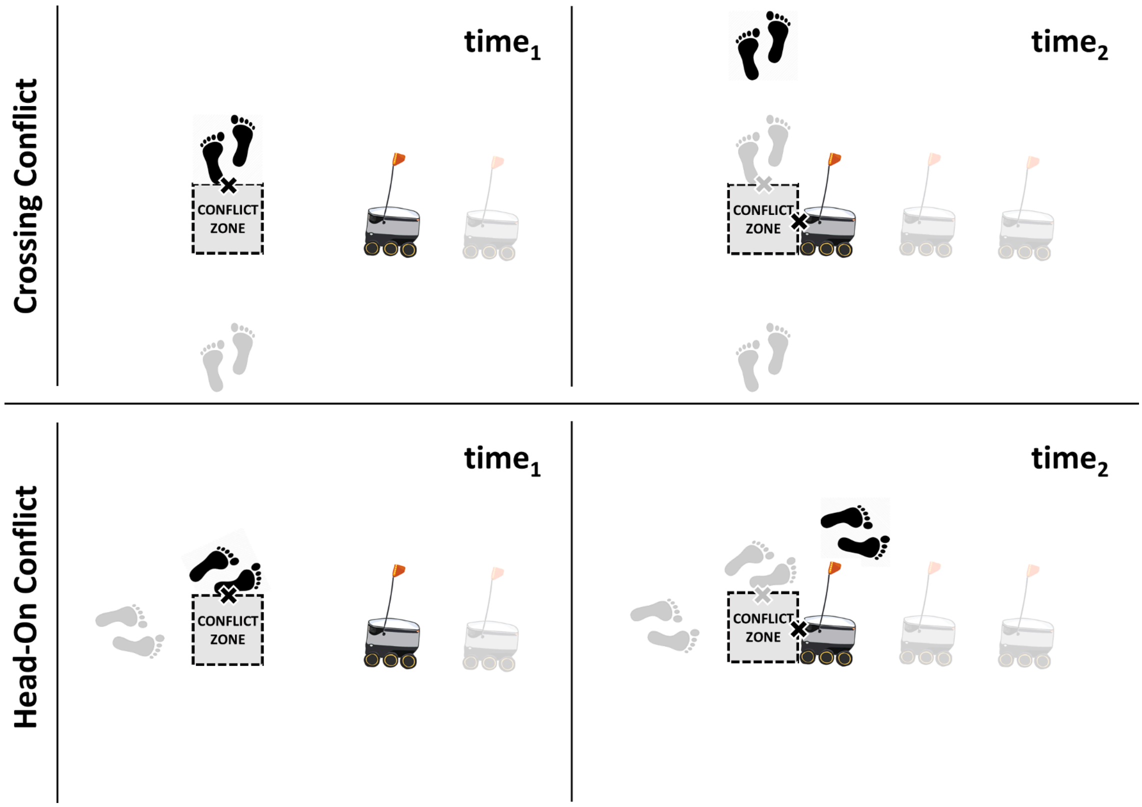

Fig. 2. Illustration of post-encroachment time (PET) measurement for two types of SADR-pedestrian conflicts.

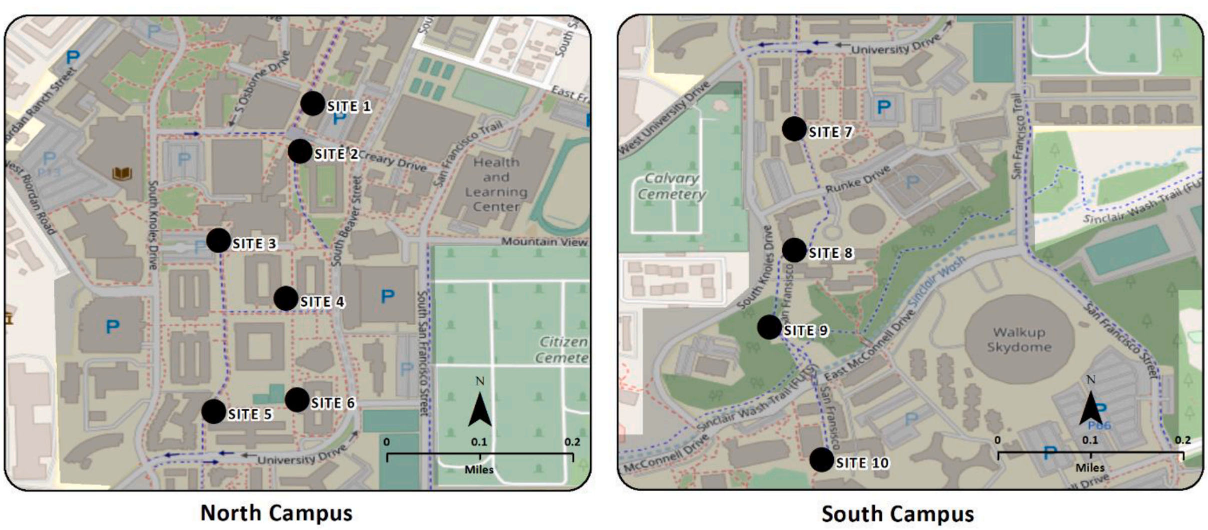

Fig. 3. Video collection sites on the north and south campus of Northern Arizona University.

conducted the following steps to help ensure internal consistency in interaction identification and associated characteristics:

- If an interaction with a recorded PET value difference less than one second was identified by two research team members, then the lower PET value was retained.
- If an interaction with a recorded PET value difference greater than one second was identified by two research team members, then the interaction was reviewed by both research team members until agreement on the PET value was reached.
- If an interaction with a recorded PET value of five seconds or less was originally identified by only one research team member, then the interaction was reviewed by both research team members until agreement on the PET value was reached (interactions with a PET value greater than five seconds were removed from the final study sample).

During the final video review phase, the two research team members assigned to review the videos for a particular site also recorded conflict-level characteristics regarding the first and second pathway user type to enter a conflict zone (SADR, pedestrian, bicyclist, other), travel direction of the second pathway user in relation to the first pathway user (same, opposite, crossing), evasive actions taken by both pathway users (no action, complete stop, deceleration, acceleration, swerve, back up), and whether the SADR-involved interaction was intentionally initiated by a human pathway user. Intentional interactions were removed from the final study sample. In the final study sample, PET values for retained SADR-involved interactions were categorized into discrete severity levels. Based on prior research (Zangenehpour et al. 2016; Russo et al., 2020), observed interactions with a PET value of 1.5 s or less were categorized as a dangerous conflict, while SADR interactions with human pathway users that produced a PET value above 1.5 s and less than or equal to three seconds were categorized as moderate conflicts. All recorded interactions with a PET value greater than three seconds were deemed to be normal interactions and not a conflict.

Spatial description of sidewalk autonomous delivery robot (SADR) interactions and observation sites

After a recognition and PET classification of SADR interactions with human pathway users was completed, a visual depiction of interaction sites and measurement of site-level characteristics was undertaken. The spatial depiction of observed SADR interactions with pedestrians and bicyclists and the dimensions of the bounding box for each site were generated within a geographic information systems (GIS) environment. A visual inspection of the location of each SADR-involved interaction in the final study sample, which were determined by a review of the field-recorded videos and subsequent manual placement in a GIS software, allowed research team members to both identify visual patterns or clusters of interactions across different severity levels and examine whether the location of recorded interactions appeared to be associated with any urban design or transportation network characteristics of a video collection site. To complement any descriptive findings resulting from the spatial inspection of SADR interactions, characteristics related to bounding box definitions were also recorded as potential predictors in a statistical model of PET severity. These site-level characteristics include the presence of a designated bike lane, the width of the sidewalk (or shared-use path), the presence of a lateral barrier (e.g., planter box) to the pathway, and the number of pathway intersections located along the perimeter of a site's designated bounding box.

Statistical analysis

A statistical analysis of different conflict- and site-level characteristics that predicted PET severity was then performed to offer further insights into the physical context and conditions associated with SADR conflicts with human pathway users. Given the limited number of unintentional SADR interactions observed in this study (n = 201), an analytic decision was made to pool the final sample to include interactions among SADRs and all human pathway users. Moreover, to offer study findings that may be more immediately translated to practitioners seeking insights into what SADR-related interactions are more worrisome to pedestrians and bicyclists than others and what factors may predict an actual conflict, the outcome variable of interest for this statistical analysis is the ordered severity level of each observed SADR-involved interaction (0 = no interaction, 1 = moderate conflict, and 2 = dangerous conflict). While the choice of thresholds to delineate the three severity levels are somewhat subjective and arbitrary, their selection can be justified by previous research (Zangenehpour et al. 2016) and analytic need for an ordered logistic regression model to meet the assumption of proportional odds. The ordered logistic model specified in this statistical analysis is expressed in Eq. (1) (Long, 1997) and is an extension of a logistic regression model applied when the dependent variable is an ordered-response with more than two discrete levels:

$$P(y_i > j) = \frac{exp\left(X_i\beta' - \phi_j\right)}{1 + exp\left(X_i\beta' - \phi_j\right)} j = 1, 2, \cdots, M - 1 \quad (1)$$

where j is the interaction severity level, X_i is a vector of observed conflict- and site-level characteristics, β is a vector of estimated parameters, ϕ_j are breakpoints associated with the severity level thresholds, and M is the number of categories of the ordered-response variables.

The final ordered logistic model for the pooled study sample was specified via a two-step process. First, the Spearman correlation value for each conflict- and site-level characteristic with the severity level outcome was calculated and all marginally significant characteristics ($p < 0.10$) were added to a full model specification. Second, a backwards elimination process was conducted to iteratively remove the predictor with the highest p-value from the previously specified model until all remaining independent variables were significant predictors of the ordered outcome variable. A subsequent estimation of the final model specification using observed SADR-involved conflict data as well as site information is intended to identify the significant conflict- and site-related determinants of more severe SADR interactions with pedestrians and bicyclists to inform mitigation and facility management strategies that guide future SADR operations.

Description of sidewalk autonomous delivery robot (SADR) interactions with pedestrians and bicyclists

A distribution of the PETs measured in this study's sample of 192 SADR interactions with pedestrians and bicyclists is shown in Fig. 4. Of note, nine interactions in the final sample (n = 201) involved an SADR and human pathway user who was not walking or bicycling (e.g., e-scooter rider). For interactions involving a pedestrian (n = 169) or bicyclist (n = 23), 106 observations were categorized as either a moderate (level 1) or dangerous (level 2) conflict. Pedestrians were involved in 38 (or 95%) of the 40 dangerous conflicts, with 12 of these level 2 interactions resulting in a PET of zero seconds. There were no observed SADR-bicyclist interactions with a PET of zero seconds, which represents either a crash between the two pathway users or an incident in which a human pathway user's body was directly above the SADR at the identified point of conflict. The two observed dangerous conflicts involving an SADR and bicyclist had a PET measurement between 1.0 and 1.5 s. Most observed SADR-bicyclist interactions were categorized as moderate conflicts (52%), while 32% SADR-pedestrian interactions were similarly categorized as level 1 interactions. For interactions visualized in Fig. 4 46% and 39% of SADR interactions with pedestrians and bicyclists, respectively, were categorized as a normal interaction (level 0).

Table 1 provides a summary of the conflict- and site-level characteristics observed in the study sample of 201 SADR interactions with human pathway users (pedestrians, bicyclists, and other users) across the 10 sampling locations. Conflict characteristics included binary variables denoting whether an SADR was the first pathway user to reach the conflict zone, travel direction of the approaching pathway users in the observed interaction, time of day in which the interaction was observed, and type of evasive action (if any) that was taken by either of pathway users involved in the observed interaction. In turn, the site characteristics collected for this study included the count and relative share of SADRs, pedestrians, and bicyclists that traversed a site's designated bounding box during 15-minute intervals that start on the hour (i.e., 9:00am to 9:15am), presence of a bike lane separated from the adjacent sidewalk, width of the sidewalk, presence of a lateral barrier adjacent to the pathway (e.g., concrete wall), and the number of pathways that intersect the bounding box at the observation site.

On average, the PET for a recorded interaction was 2.79 s. Regarding the time of day, most of the sampled interactions between SADRs and human pathway users occurred during the afternoon (68%), which was also the longest of the three daily observation periods. In most interactions (57%), the SADR was the first pathway user to reach the

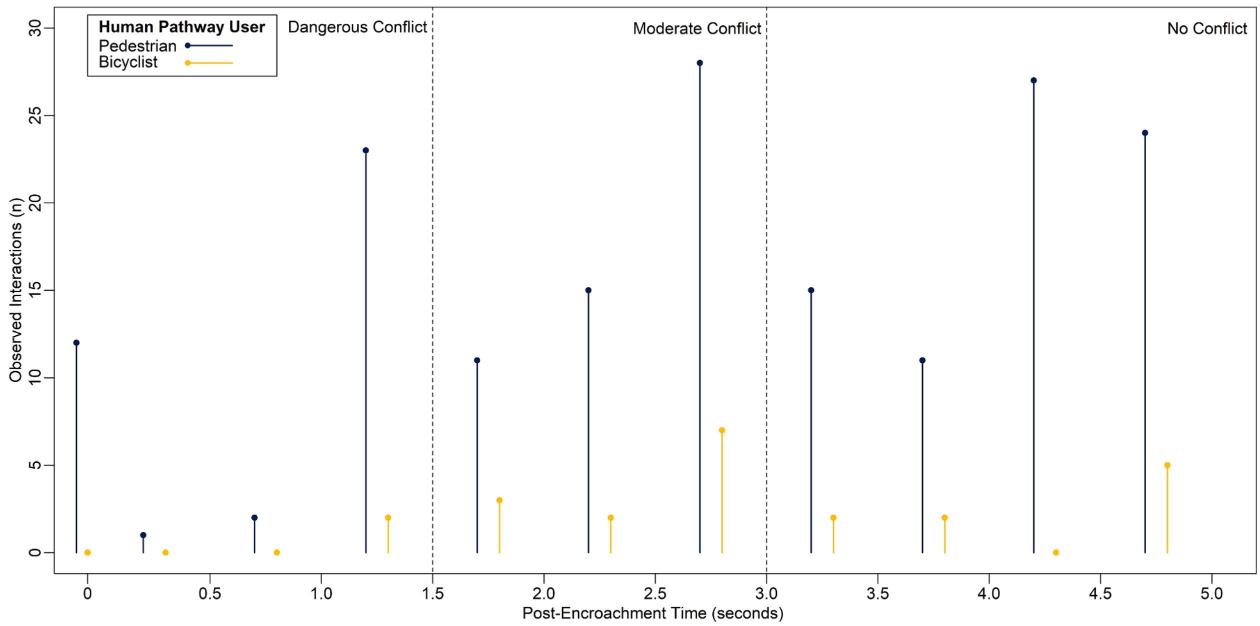

Fig. 4. Distribution of observed SADR-involved interactions with human pathway users by conflict severity levels.

conflict zone and thus deemed to have initiated the conflict with the human pathway user. Of the three types of interactions captured in our study, nearly one half (47%) were crossing conflicts, with the remaining interactions either signifying a head-on meeting in which the two pathway users were traveling in opposite directions (37%), or one pathway user was attempting to overtake another pathway user traveling in the same direction (15%).

Irrespective of conflict type, 44% of those pathway users who initiated an interaction were found to have taken no action, while only one third (33%) of pathway users who were second to the conflict point were observed to have not taken any evasive actions. The most common evasive action observed in SADR conflicts with human pathway users was an abrupt change in direction (swerve), with 35% and 30% of first and second pathway users, respectively, observed to have taken this action in an interaction. Ten percent of first and second pathway users in an observed interaction chose to decelerate in avoidance of a crash, while it was more common for the second pathway user to a conflict point to make a complete stop (26%) than the pathway user who initiated the interaction (10%). In turn, only 1% of the first or second pathway users to reach the conflict point accelerated their travel speed to avoid any crash, with no pathway users in an interaction found to have reversed their travel direction (not shown in Table 1). Generalizing the above descriptive findings, the average interaction was classified as a moderate conflict (level 1) in which the SADR initiated the conflict with a human pathway user by crossing in front of the path taken by the pedestrian or bicyclist, with both pathway users likely to have taken some evasive action to avoid a crash.

In complement to the above evasive maneuver summary of the study sample used for statistical modeling, Table 2 offers a cross-tabulation of the evasive maneuvers taken in SADR interactions of varying levels of PET classification for the first and second pathway users to reach a conflict point. Regarding interactions between SADRs and pedestrians in which the SADR was first to the conflict point (pathway user 1), the pedestrian was less likely to make an evasive action as the PET measurement neared zero seconds. This outcome may be the result of the pedestrian not recognizing the approaching SADR, recognizing that the SADR has made the evasive maneuver, or anticipating that the path of the SADR will not result in a crash. Regardless of the interaction type, the most popular evasive action taken by the pedestrian when the SADR reached the conflict point first was to swerve. For SADR-pedestrian interactions that were initiated by a pedestrian (44% of all SADR-pedestrian interactions), the pedestrian swerved from the SADR in every dangerous conflict, 78% of moderate conflicts, and 65% of interactions where no conflict was determined.

Akin to SADR interactions with pedestrians, most bicyclist interactions with SADRs (61%) were initiated by the non-human pathway user, with the two dangerous conflicts observed in this sample characterized by a robot reaching the conflict point first. No action was taken by the bicyclist in either of the two dangerous conflicts, with two-thirds of bicyclists in observed moderate conflicts (n = 6) and normal interactions (n = 2) similarly conducting no evasive maneuver. If an evasive action was taken by a bicyclist in a level 1 or level 0 incident initiated by an SADR, that bicyclist was observed to have abruptly changed direction. In all three observed moderate conflicts where a bicyclist reached the identified conflict point before the SADR, the bicyclist was found to have swerved. For the remaining six SADR-bicyclist interactions (no conflict) where a bicyclist initiated an interaction, there were four (67%) occasions in which the human pathway user took no evasive action.

By examining site characteristics associated with the study sample of observed interactions (Table 1), insights into the context surrounding SADR-related conflicts with human pathway users can be offered. Across all study observations, the average interaction occurred in a 15-minute window of video review in which 100 pedestrians, 20 bicyclists, and seven SADRs were enumerated at the particular site. On average, the site with the observed conflict had a dedicated bike lane (86%) and a sidewalk width that was at least 10 feet (82%), with little presence of a lateral pathway barrier (1%). One third (33%) of interactions noted in this study occurred inside a bounding box with three or more intersections, while 45% of all recorded interactions were observed at a site with one or two pathway intersections.

Description of sites with sidewalk autonomous delivery robot (SADR) interactions

A site-by-site overview of the 10 sampling locations is provided in Table 3, with details on characteristics of the pathways as well as 15-minute counts of observed pathway users and interactions between SADRs and pedestrians, bicyclists, and other human travelers. Regarding the site characteristic of sidewalk width, three of the north campus video

Table 1
Descriptive statistics of observed sidewalk autonomous delivery robot (SADR) conflicts.

Variable	Mean	SD	Min	Max
Post-encroachment time (seconds)	2.79	1.30	0	5
Conflict Characteristics				
Robot first to conflict	0.57	0.50	0	1
Conflict direction: Same	0.15	0.36	0	1
Conflict direction: Opposite	0.37	0.48	0	1
Conflict direction: Crossing	0.47	0.50	0	1
Time of day: Morning (9:00am-10:30am)	0.12	0.33	0	1
Time of day: Afternoon (11:00am-2:00 pm)	0.68	0.47	0	1
Time of day: Evening (4:30 pm-6:00 pm)	0.20	0.40	0	1
Evasive maneuver (Pathway user 1): No action	0.44	0.50	0	1
Evasive maneuver (Pathway user 1): Complete stop	0.10	0.30	0	1
Evasive maneuver (Pathway user 1): Deceleration	0.10	0.29	0	1
Evasive maneuver (Pathway user 1): Acceleration	0.01	0.10	0	1
Evasive maneuver (Pathway user 1): Swerve	0.35	0.48	0	1
Evasive maneuver (Pathway user 2): No action	0.33	0.47	0	1
Evasive maneuver (Pathway user 2): Complete stop	0.26	0.44	0	1
Evasive maneuver (Pathway user 2): Deceleration	0.10	0.30	0	1
Evasive maneuver (Pathway user 2): Acceleration	0.01	0.07	0	1
Evasive maneuver (Pathway user 2): Swerve	0.30	0.46	0	1
Site Characteristics				
Exposure (15-min window): Robots	6.93	3.72	0	18
Exposure (15-min window): Pedestrians	100.90	88.85	5	634
Exposure (15-min window): Bicyclists	19.51	14.56	0	57
Exposure (15-min window) share: Robots	0.08	0.07	0.00	0.34
Exposure (15-min window) share: Pedestrians	0.70	0.14	0.06	0.95
Exposure (15-min window) share: Bicyclists	0.15	0.08	0.00	0.40
Presence of bike lane	0.86	0.35	0	1
Sidewalk width: Less than 10 feet	0.17	0.38	0	1
Sidewalk width: 10–20 feet	0.48	0.50	0	1
Sidewalk width: 20 feet or more	0.34	0.48	0	1
Presence of lateral pathway barrier	0.01	0.12	0	1
Pathway intersections: 0	0.22	0.41	0	1
Pathway intersections: 1	0.17	0.38	0	1
Pathway intersections: 2	0.28	0.45	0	1
Pathway intersections: 3	0.33	0.47	0	1

collection areas (sites 1, 2, and 5) and three of the south campus areas (sites 7, 8, and 10) had sidewalks wider than 15 feet. However, both site 4 (north campus) and site 9 (south campus) had sidewalk widths less than 10 feet. Each of the two latter sites had designated bike lanes and no pathway intersections within their selected bounding boxes. Separated bike lanes in which SADRs are not programmed to travel within existed at eight of the video collection sites, with the exceptions of sites 6 (north campus) and 9 (south campus). Akin to site 9, the bounding box at site 6 also did not capture any pathway intersections, which was also characteristic of sites 2, 4, and 7. Site 7 was the only video collection area to have a vertical barrier adjacent to its pathway. Only three of the sites had more than one pathway intersection, with sites 3 and 10 having two intersecting paths and site 5 having three intersections.

In general, the highest volume of pedestrians was observed on the six north campus sites, ranging from 244 pedestrians per hour at site 5 to 975 pedestrians per hour at site 1. All sites on the southern portion of campus, which has fewer academic buildings, had lower pedestrian exposure counts than north campus sites, with the exception of site 9 (304 pedestrians per hour). In terms of bicyclist exposure counts, the distribution was more balanced across the north and south campus sites. Sites 4 and 6 on north campus had the fewest observed bicyclists, with one-hour exposure counts of 13 and 26 bicyclists, respectively. North campus sites 1 and 2, however, had the highest exposure counts for bicyclists, with one-hour averages at each site slightly above 100 bicyclists, whereas the highest count of bicyclists on south campus was observed at site 9 (76 bicyclists per hour). Turning to SADR counts, sites 1 and 2, which are located to the north of most campus dining options and on-campus residences, had the fewest recorded SADRs (about 10 SADRs per hour), while sites 8 and 9, which are located along a multi-use path connecting the south campus student union and several on-campus dormitories, had the highest recorded count of SADRs (24 and 28 SADRs per hour, respectively).

Through a site-level investigation of SADR interactions with pedestrians, site 5 was found to have the most total interactions (n = 55), with 16 of these interactions categorized as moderate conflicts and another 14 interactions categorized as being dangerous conflicts. Site 5 was also the location of one of the two SADR-bicyclist level 2 interactions observed in this study. Fig. 5 offers a visualization of the location of these SADR-pedestrian and SADR-bicyclist interaction locations, distinguished across the three PET categories. At site 5, all pedestrian and bicyclist interactions with SADRs occurred on sidewalks, which are the facilities that these food delivery services are programmed to traverse. However, clusters of interactions are found at the three

Table 2
Evasive maneuvers of pedestrians and bicyclists in sidewalk autonomous delivery robot (SADR) conflicts.

Pedestrian Interactions:	Pathway User 1: SADR			Pathway User 2: SADR		
Pedestrian's Evasive Maneuver	Dangerous Conflict	Moderate Conflict	No Conflict	Dangerous Conflict	Moderate Conflict	No Conflict
No action	14	14	10	0	3	15
Complete stop	2	0	1	0	0	0
Deceleration	1	2	0	0	0	0
Acceleration	0	0	0	0	1	1
Swerve	11	20	20	10	14	30
Back-up	0	0	0	0	0	0
Total Interactions	*28*	*36*	*31*	*10*	*18*	*46*
Bicyclist Interactions:	Pathway User 1: SADR			Pathway User 2: SADR		
Bicyclist's Evasive Maneuver	Dangerous Conflict	Moderate Conflict	No Conflict	Dangerous Conflict	Moderate Conflict	No Conflict
No action	2	6	2	0	0	4
Complete stop	0	0	0	0	0	0
Deceleration	0	0	0	0	0	0
Acceleration	0	0	0	0	0	0
Swerve	0	3	1	0	3	2
Back-up	0	0	0	0	0	0
Total Interactions	*2*	*9*	*3*	*0*	*3*	*6*

Table 3
Video collection site characteristics and observed exposure and interaction information.

Site	Site Characteristics		15-minute Exposure Counts					Observed SADR Interactions			
1	Sidewalk width (ft)	19.0		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	2.2	243.7	26.3	17.5	Ped	8	1	2
	Lateral path barrier	No	Min	0	30	5	1	Bike	0	0	0
	Path intersections	1	Max	7	938	90	51	Other	0	0	0
2	Sidewalk width (ft)	19.4		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	2.2	209.4	26.9	17.5	Ped	0	0	0
	Lateral path barrier	Yes	Min	0	17	3	2	Bike	0	0	0
	Path intersections	0	Max	9	746	109	51	Other	0	0	0
3	Sidewalk width (ft)	11.2		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	2.3	107.1	18.3	4.6	Ped	10	8	5
	Lateral path barrier	No	Min	0	11	2	0	Bike	2	2	1
	Path intersections	2	Max	9	228	59	16	Other	1	0	0
4	Sidewalk width (ft)	6.9		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	3.0	123.4	6.4	4.5	Ped	3	1	0
	Lateral path barrier	No	Min	0	24	1	1	Bike	0	1	0
	Path intersections	0	Max	9	373	25	13	Other	0	0	0
5	Sidewalk width (ft)	20.7		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	5.4	61.0	18.6	8.8	Ped	25	16	14
	Lateral path barrier	No	Min	0	5	4	0	Bike	2	3	1
	Path intersections	3	Max	17	174	70	53	Other	2	1	2
6	Sidewalk width (ft)	12.5		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	No	Mean	3.4	84.4	3.3	1.7	Ped	6	4	8
	Lateral path barrier	No	Min	0	27	0	0	Bike	2	2	0
	Path intersections	0	Max	12	253	10	6	Other	1	0	0
7	Sidewalk width (ft)	20.9		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	4.9	39.5	12.3	4.8	Ped	1	1	1
	Lateral path barrier	Yes	Min	1	15	2	0	Bike	0	0	0
	Path intersections	0	Max	11	86	34	15	Other	0	0	0
8	Sidewalk width (ft)	15.4		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	7.0	55.3	15.9	7.6	Ped	13	6	5
	Lateral path barrier	No	Min	0	13	0	1	Bike	1	2	0
	Path intersections	1	Max	18	171	53	33	Other	1	0	0
9	Sidewalk width (ft)	9.8		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	Yes	Mean	6.1	76.0	18.9	9.3	Ped	9	17	3
	Lateral path barrier	No	Min	0	25	4	1	Bike	0	1	0
	Path intersections	0	Max	17	219	58	30	Other	0	0	0
10	Sidewalk width (ft)	18.0		SADR	Ped	Bike	Other		PET = 0	PET = 1	PET = 2
	Separated bike lane	No	Mean	3.9	18.4	11.4	6.0	Ped	2	0	0
	Lateral path barrier	No	Min	0	2	2	0	Bike	2	1	0
	Path intersections	2	Max	14	59	36	24	Other	1	0	0

intersecting paths, with a set of dangerous conflicts observed at the two corners of the service road located to the west which intersects the main shared-use facility. Other SADR-pedestrian interactions categorized as dangerous conflicts are located south of the intersecting service road near the entrance to the academic building and along the eastern sidewalk between the two other intersecting paths. In terms of SADR-bicyclist interactions, multiple interactions are found in the northwestern corner of the bounding box, which is also the site of a bike parking corral.

A further examination of Table 3 reveals that site 9, which had the second highest volume of SADRs and second narrowest sidewalk width of the ten video collection sites, had the second highest count of SADR-pedestrian interactions (n = 29). Sites 3 and 8 also had more than 20 SADR-pedestrian interactions, with each site having at least one pathway intersection and being on the lower-half of sites in terms of sidewalk width. Site 6, in turn, was found to have the second most level 2 SADR-pedestrian conflicts, with this site having no pathway intersections but also no separated bike lane and a sidewalk width of 12.5 feet. Site 6 was also found to have the third highest number of SADR-bicyclist conflicts, which may be due to a mixing of all pathway users on this narrow shared-use facility. Meanwhile, site 3, which has a separated bike lane but two pathway intersections, had the second highest number of SADR-bicyclist interactions (n = 5). Of note, the two sites with the greatest volumes of bicyclists (sites 1 and 2) had no recorded SADR-bicyclist interactions despite having comparable SADR volumes to site 3. Descriptively, this study finding along with the absence of observed SADR-bicyclist interactions at site 7 may be related to the presence of separated bike lanes, wider sidewalks, and limited path intersections that when taken together signify ample space for overtaking actions and minimal opportunities for SADR routes to cross human pathway user routes.

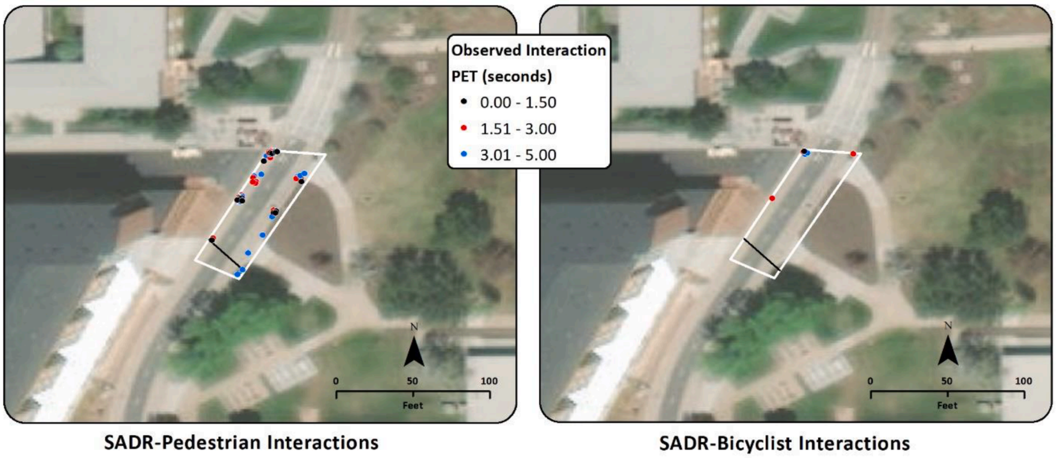

Fig. 5. Spatial depiction of SADR-involved interactions with pedestrians and bicyclists at site 5.

Modeled determinants of sidewalk autonomous delivery robot (SADR) interaction severity

Results of the ordered logit model of SADR interactions with pedestrians, bicyclists, and all other human pathway users are detailed in Table 4. The final model revealed a statistically significant improvement over the constants only model ($\chi^2 = 28.72$, $p < 0.001$), with three predictors related to conflict characteristics that generally agreed with the descriptive statistics of the aggregate data set. The estimated parameters (betas) of each significant predictor reflects the log odds of that characteristic related to the PET severity level of an observed SADR-involved interaction. Extrapolating model results of observed SADR interactions, the severity of SADR-involved interactions tended to increase if the robot was the first pathway user to reach the conflict point. As previously mentioned, a majority of interactions observed in the study sample were initiated by the SADR pathway user. Model results also found that the evasive action of the first pathway user to reach an identified conflict point was more likely to be a swerve in travel direction as the PET associated with an interaction neared zero seconds. Descriptively, if an SADR-pedestrian interaction (the most commonly observed interaction) initiated by an SADR was defined as a moderate or dangerous conflict, then the robot was more likely to swerve rather than take no evasive action. Finally, model results suggested that the severity of an SADR interaction decreased if the robot and the human pathway user were traveling in opposite directions. This model finding is likely attributable to the increased likelihood that a human pathway user can see the approaching SADR from a safe distance and make a normal adjustment to their travel trajectory.

Table 4
Ordered logit model results.

Variable	Beta	SE	CI: 2.5%	CI: 97.5%
Conflict Characteristics				
Robot first to conflict	1.75	0.39	1.01	2.55
Conflict direction: Opposite	−0.71	0.34	−1.38	−0.05
Evasive maneuver (Pathway user 1): Swerve	1.00	0.44	0.15	1.89
Intercepts				
Threshold: 0 and 1	0.91	0.37		
Threshold: 1 and 2	2.59	0.40		
Model Summary				
Number of observations	201			
Log likelihood	−196.91			
Log likelihood (constants only)	−211.26			
Akaike information criterion	403.81			

Discussion

This study helps identify the traffic safety concerns of pedestrians and bicyclists who share pathways with SADRs and offers evidence into the challenges of operating these new last-mile delivery technologies in a real-word setting. Specifically, by recognizing the most common types and patterns of SADR interactions with pedestrians and bicyclists, improvements in SADR route selection and facility management practices that strive to reduce the number and severity of SADR-related conflicts with human pathway users can be pursued by private autonomous food delivery service providers and public sector counterparts including transportation planners and engineers. In examining the spatial distribution of observed interactions and the statistical modeling results, SADR-pedestrian conflicts tended to cluster at intersections of sidewalks and other non-motorized pathways and occurred when an SADR was crossing in front of or overtaking a pedestrian on a sidewalk. To help reduce the prevalence of crossing conflicts, SADR routes that prioritize the parallel travel of these devices along pedestrian corridors and minimize the number of high-activity sidewalk crossings should be programmed whenever possible. In turn, SADR routing decisions must factor in the width of sidewalks used by these devices to ensure adequate space is available for an SADR to safely overtake a slower moving pedestrian without changing the human pathway user's trajectory. In instances where a common trip destination cannot be served without an SADR traveling on a sidewalk designed for one pedestrian in each travel direction, actions to widen the sidewalk should be considered.

While an extensive pedestrian network spans most of NAU's main campus, there is less dedicated infrastructure for bicyclists who often share facilities principally designed for pedestrians or motorists. In this study, SADR interactions with bicyclists were common where bike network gaps exist and bike parking facilities are located. In response, modifications to or considerations in SADR routes that favor placing the autonomous technology on the side of the shared-use path that produces the fewest turning movements for a bicyclist should be pursued when dedicated bike infrastructure is not present. Site-level examination should be given to locations along well-traversed bicycling routes where a bicyclist must transition from a dedicated facility (e.g., bike lane), where SADR use is not authorized, to a sidewalk shared by pedestrians as well as SADRs and an ever-increasing share of other micromobility options (e.g., e-scooters). Regarding the grouping of observed SADR-bicyclist interactions near bike parking facilities—visualized in Fig. 5, the positioning of SADR delivery points away from main building entrances with nearby bike racks or bike lockers to alternative building entryways should be prioritized to reduce opportunities for SADR-bicyclist interactions. The introduction of designated SADR delivery stations delineated by physical path markings and warning signs as a curb management strategy would provide further information to nearby bicyclists about the presence of SADRs in the area.

Aside from modifications to SADR-related routing programs and facility management practices, this real-world analysis of SADR conflicts with pedestrians and bicyclists also underscores a need for future changes in the design of these self-driving food delivery devices and development of warning signs noting their local presence to human pathway users. The identification of unintentional SADR interactions with human pathway users in our study that were deemed to be dangerous conflicts—including 12 interactions with a PET value of zero seconds—confirms that these new autonomous technologies are disrupting travel as a pedestrian or bicyclist despite any initial best effort by SADR service providers to seamlessly introduce these autonomous devices on pathways designed for our transportation system's most vulnerable users. In response, further advancements in the design of SADRs that improves their visual and audible detection by human pathway users should be considered with future models. At present, Starship robots deliver a 'chirping' noise when in proximity to a human pathway user. However, in areas of higher traveler volumes or those with a confluence of sidewalks and shared-use paths, this audible cue may be given too late for an approaching bicyclist, e-scooter rider, or wheelchair user traveling at a greater speed than a pedestrian to make any required evasive maneuver. Accordingly, the instruction for SADRs to generate audible cues when traveling through designated high-activity zones identified by contracting partners or via built-in detection sensors may offer safety benefits to a wider range of human pathway users. As a complement, caution or warning signs should be introduced to alert designated human pathway users to the increased potential for interaction with SADRs in these high-activity zones.

Although the development of such warning signs is likely to reduce possible SADR conflicts with active transportation adopters, public agencies seeking to introduce emerging or novel methods for last-mile food deliveries in the near future should be cognizant of placing further hardships on pedestrians or bicyclists who at present face increased constraints on safe travel in urban settings due to the popularity of ridesourcing and food delivery services on roadways and micromobility options on already-crowded sidewalks. Accordingly, as SADR technology providers such as Starship and Kiwibot look to expand their markets beyond college campuses to meet a growing demand for online food delivery services, attention should be given to vehicle design improvements that increase their detection across a more heterogenous population and built environment. These design considerations should include the requirement of greater lighting to meet the likelihood of SADRs traveling during evening hours or inclement weather conditions as well as alterations to vehicle profiles to both meet the likely increased demand for larger food deliveries (e.g., groceries) and improve their visibility to human pathway users who may not easily detect a vehicle that is less than two feet in height within their traveling sightlines.

Conclusions

This study represents an early investigation into the impacts of autonomous food delivery robots sharing pathways with pedestrians and bicyclists, with its findings providing needed evidence on the traffic safety conditions experienced by active travelers interacting with SADRs in a real-world setting. An immediate contribution of this study is its offering of insights to planners, engineers, and policymakers who seek facility management strategies capable of supporting the safe introduction of this emerging autonomous freight technology on shared-use facilities in urban settings. Potentially successful mitigation strategies can be derived from this study's spatial description of SADR-involved interactions with pedestrians and bicyclists, which found that moderate and dangerous conflicts cluster near sites with intersecting and narrow pathways without any delineation of what space travelers should occupy. Statistical model results found that the PET-measured severity of an SADR-involved interaction with an active traveler tended to increase when an SADR crossed the intended trajectory of the human pathway user, with the pedestrian or bicyclist often altering their path to avoid a collision. These study findings suggest the safe introduction of SADRs onto already-crowded urban pathways and curb spaces will be a challenge for practitioners likely to require innovative solutions related to SADR route programming, public education, and a redesigning of urban infrastructure.

Methodological contributions aimed at guiding future research using SSMs to understand traffic safety conditions attributed to autonomous devices without well-defined travel lanes are also made with this study. To identify SADR interactions with active travelers, this study established an adapted PET metric that requires the creation of a site-level, static bounding box and a user-level, dynamic conflict zone. The former geography is customary to PET analyses exploring vehicle-based interactions, which are generally contained within delineated travel lane(s), while the second geography operates as a nested bounding box capable of defining incidents involving pathway users with physical dimensions narrower than their travel lane(s) or which travel on shared-use facilities. This study's adaptation of an existing SSM to explore how smaller emerging autonomous freight delivery devices interact with pedestrians and other sidewalk users could foreseeably be transferred to study the possible impacts that new road autonomous delivery robots would have on motor vehicles when traveling on facilities designed for use by the latter user type.

While this study offers contributions toward improving any present understanding of how traffic safety conditions for pedestrians and bicyclists are being altered via the introduction of SADRs, there are notable study limitations that should be addressed with future research. First, while the introduction of Starship's SADR fleet to NAU's main campus provided a real-world setting to undertake this research, the landscape and traveler composition attributed to a college campus does not represent the urban context or general population that is likely to experience any future, large-scale deployment of autonomous food delivery services. Second, although this study's video data collection effort generated a mostly balanced distribution of SADR-involved interactions across severity levels, the sample had fewer dangerous conflicts than the other two interaction categories, which limited the statistical power of the models. Relatedly, the division of PET severity categories based on prior studies of motor vehicle-involved interactions could be revisited in future research as SADRs travel at a reduced speed and their operation in a shared-use setting may lead to more frequent, close interactions with pedestrians and bicyclists. Finally, the study sample of SADR-involved interactions removed any conflict initiated by a human pathway user; however, some pedestrians and bicyclists may have greater comfort traveling in proximity to SADRs. Any such individual-level variation in comfort is likely to skew the sample toward interactions with a lower, non-zero PET and greater observed severity level, and cannot be fully comprehended without an investigation into how different market segments react to the introduction of SADRs on pathways shared by pedestrians and bicyclists.

CRediT authorship contribution statement

Steven R. Gehrke: Conceptualization, Methodology, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Funding acquisition. **Christopher D. Phair:** Data curation, Formal analysis, Writing – original draft, Visualization. **Brendan J. Russo:** Conceptualization, Methodology, Formal analysis, Writing – original draft. **Edward J. Smaglik:** Conceptualization, Methodology, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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