Evaluation of Sidewalk Autonomous Delivery Robot Interactions with Pedestrians and Bicyclists

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A Research Report from the Pacific Southwest Region University Transportation Center

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16. Abstract

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About the Pacific Southwest Region University Transportation Center

The Pacific Southwest Region University Transportation Center (UTC) is the Region 9 University Transportation Center funded under the US Department of Transportation's University Transportation Centers Program. Established in 2016, the Pacific Southwest Region UTC (PSR) is led by the University of Southern California and includes seven partners: Long Beach State University; University of California, Davis; University of California, Irvine; University of California, Los Angeles; University of Hawaii; Northern Arizona University; Pima Community College.

The Pacific Southwest Region UTC conducts an integrated, multidisciplinary program of research, education and technology transfer aimed at *improving the mobility of people and goods throughout the region.* Our program is organized around four themes: 1) technology to address transportation problems and improve mobility; 2) improving mobility for vulnerable populations; 3) Improving resilience and protecting the environment; and 4) managing mobility in high growth areas.

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Disclosure

Steven R. Gehrke (Principal Investigator), Brendan J. Russo (Co-Principal Investigator), and Edward J. Smaglik (Co-Principal Investigator) conducted this research titled, "Evaluation of Sidewalk Autonomous Delivery Robot Interactions with Pedestrians and Bicyclists" at Northern Arizona University. The research took place from August 15, 2021 to August 14, 2022 and was funded by a grant from the Pacific Southwest Region University Transportation Center in the amount of $97,421. The research was conducted as part of the Pacific Southwest Region University Transportation Center research program.

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Abstract

Information and communication technology advancements and an increased demand for contactless deliveries after the Covid-19 pandemic outbreak have resulted in the growing adoption of automated delivery services. Across university campuses, the deployment of sidewalk autonomous delivery robots (SADRs) has provided students, staff, and faculty a convenient last-mile delivery option. However, SADRs traverse campuses on paths designed for pedestrians and bicyclists, which could potentially result in conflicts among different pathway users and unsafe travel conditions. This report—comprising two studies—offers evidence on the objective safety and perceived comfort experienced by pedestrians and bicyclists interacting with SADRs on multi-use paths. In the first study, SADR interactions with human pathway users observed via field-recorded video collected at Northern Arizona University (NAU) campus were examined by employing the surrogate safety measure of post-encroachment time. The second study analyzed the reported comfort of SADR-involved interactions filmed from pedestrian and bicyclist perspectives and collected via the administration of a survey instrument to an NAU population with experience in the adoption of automated food delivery services and SADR-involved interactions. This report's findings are intended to help inform new facility management strategies that support the safe introduction of SADRs on shared-use facilities in current and future settings.

Research Report

Executive Summary

Advancements in information and communication technologies coupled with public health concerns regarding Covid-19 transmission have sparked the introduction and growing demand for automated delivery services. On university campuses, sidewalk autonomous delivery robots (SADRs) have emerged in recent years as a last-mile freight service for students, faculty, and staff seeking the convenience of an on-demand delivery of meals or drinks to their residence or workplace. The commercial deployment of SADRs on American campuses, which occurred at Northern Arizona University (NAU) in March 2019, has grown in popularity due largely to the extensive pedestrian networks and population of technology-savvy, young adults found in these settings. However, amongst this population segment and in these physical contexts, walking and bicycling is also common and may be hindered by the addition of SADRs on sidewalks and shared-use pathways primarily designed for pedestrians and bicyclists.

This research project aims to provide early evidence on the observed and reported transportation safety concerns experienced by pedestrians and bicyclists who interact with SADRs along shared-use pathways on NAU's campus. In this project's first of two studies, five days of field-recorded videos were collected from 10 shared-use sites, with the frequency, location, and severity of SADR-involved interactions with human pathway users determined by adapting the surrogate safety measure of post-encroachment time (PET) to account for pathway user movements and trajectories at sites with ambiguity regarding travel lanes. The locations of observed SADR-involved interactions were then spatially depicted in relation to their physical context, while an ordered logit regression model of their PET-measured severity level was estimated as a function of conflict- and site-level characteristics. In the second study, self-reported data on SADR-related experiences and perceived comfort in sharing pathways with SADRs as an active traveler were collected by administering a tablet-based survey instrument to a convenient sample of the NAU population. The reported comfort levels were recorded as five-point Likert scale responses to four stated choice experiments that visualized a pedestrian or bicyclist making an evasive maneuver to avoid a collision with an oncoming SADR at two PETs, with these ordered outcome variables then modeled as a function of the socioeconomic attributes and SADR-related experiences of the survey's respondents.

Select findings from these two studies, which can help inform future research and practice related to the safe introduction or continued operation of SADRs in shared-use transportation settings, include:

- Moderate and dangerous SADR-involved conflicts tend to cluster near sites with intersecting and narrow pathways without any delineation of what space human pathway users should occupy.
- PET-measured severity of an SADR-involved interaction with a pedestrian or bicyclist tended to increase when an SADR was found to cross the human pathway user's intended trajectory, with the pedestrian or bicyclist often taking an evasive action to avoid an SADR-involved collision.
- While pedestrians were generally more comfortable than bicyclists in sharing paths with SADRs, individuals who reported discomfort in sharing paths with SADRs as a pedestrian or altered their paths in the past because of SADRs were less comfortable needing to evade an oncoming SADR.
- Individuals who have frequently adopted autonomous food delivery services in the past tended to be more comfortable in taking evasive actions as a pedestrian or bicyclist to avoid potentially more-severe interactions with SADRs.

Introduction

In March 2019, Northern Arizona University (NAU) became the second college campus in the United States to deploy a fleet of sidewalk autonomous robot delivery (SADR) vehicles capable of transporting meals and drinks from on-campus restaurants to its buildings and dormitories by an app-based request from faculty, staff, and students. Operated by Starship Technologies, these new low-speed automated delivery services utilize machine learning techniques, artificial intelligence recognition, and a suite of sensors to traverse shared-use paths on the NAU campus at a travel speed of four miles per hour (Figure 1). The introduction of this new last-mile delivery freight technology brought immediate benefits related to consumer convenience and expanded meal access, while pressing concerns of climate change and the onset of the Covid-19 pandemic have placed a global spotlight on the importance of autonomous and electric delivery robots as a valuable step toward low-carbon and contactless freight delivery. However, SADR fleets presently operate on sidewalks and shared-use paths that were previously designated for exclusive use by pedestrians, bicyclists, and other human pathway users; therefore, creating potentially unsafe travel conditions among pathway users and ultimately traffic safety concerns for active travelers.

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

This research report, which is composed of two studies, investigates the objective and perceived safety concerns experienced by pedestrians and bicyclists traveling on shared-use paths with SADRs on NAU's campus. In the first study, one week of field-recorded video from ten locations across the NAU campus were collected to offer baseline knowledge of 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 first study, which provides initial real-world insights into the safety impacts of SADRs sharing pathways with pedestrians and bicyclists, are intended to help inform facility management strategies that are capable of supporting the safe introduction of these low-speed automated freight devices on multimodal transportation facilities in current and future settings.

In the second study, an original survey instrument was developed and administered to an NAU college population with real-world experience in the use of automated food delivery services and interaction with SADRs as active travelers. The survey instrument collected individual characteristics and responses to stated choice experiments of SADR-involved interactions from the perspectives of pedestrian and bicyclist. This study design permitted the identification of personal attributes and SADR-related experiences or perceptions that are associated with self-reported comfort in sharing pathways with SADRs from the perspective of an active traveler. Findings from this second study, which describes the profile of SADR service adopters and analyzes the reported level of comfort that individuals in a real-world setting of SADR deployment have with this emergent freight technology as an active traveler, are intended to bolster a nascent evidence base on the use of emerging automated delivery robots and their possible safety impacts for pedestrians and bicyclists who share their transportation facilities.

The design, implementation, and findings from each of these studies are described in the following two chapters of this report, which then concludes with a synthesis of this research report's contributions.

Study 1: Observed Sidewalk Autonomous Delivery Robot Interactions with Pedestrians and Bicyclists on Shared-Use Pathways

Background

In 2019, Starship Technologies first launched a commercial fleet of autonomous food delivery services on American college campuses (*1*). 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, sensors, and artificial intelligence capabilities that permit a mapping of its physical context and the application of its advanced object-detection system while traveling at four miles per hour (NAU 2019). The ability of these sidewalk autonomous delivery robots (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. 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 (*2*). 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 also meant greater opportunity for unwelcomed conflict and further obstructions along ever-popular curbside spaces.

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 (*3*), 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 initial 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 a crash have supported the use of SSMs as an alternative for identifying and analyzing traffic safety issues, especially those which concern pedestrians and bicyclists (*4*). Post encroachment time (PET) is one SSM that permits an evaluation of the severity of a traffic incident based on the immediacy in which a crash was avoided (*5*). 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 (*6*). While early PET applications centered on the study of vehicle traffic safety, 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 (*7*) and a 12-hour analysis of interactions amongst pedestrians and bicyclists (traditional and electric) in Shenzhen, China (*8*). 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 SADRs in shared-use environments.

Past studies have adopted PET as a SSM to assess vehicle-pedestrian conflicts. Chen et al. (*9*) 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 2,473 pedestrians and 2,897 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 (*9*). In a second study, Ni et al. (*10*) evaluated video collected at three intersections in Shanghai, China that encompassed a total of 1,144 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 (*10*). 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 (*11*).

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. (*12*) evaluated 1,514 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. Results from this study, which categorized interactions as normal, conflicts, or dangerous conflicts based on calculated PET value, found that bicycle and vehicle speed along with select human pathway user factors predicted an increase in conflict severity (*12*). Another Montreal-based study (*13*), which collected 90 hours of video from 23 intersections to evaluate the effectiveness of bike lanes in protecting bicyclists from turning vehicles, also categorized interactions based on PET values: very dangerous (PET ≤ 1.5s), dangerous (1.5s

< PET ≤ 3s), mild (3s < PET ≤ 5s) and no interaction (PET > 5s). The study's estimation of ordered logistic regression models specifying site-level characteristics including bicyclist exposure and bike lane conditions found higher PET values (i.e., safer traffic conditions) when bike lanes were located on the left side of vehicular traffic rather than the opposing side (*13*). The adoption of PET and other SSMs has been operationalized in other traffic safety research including a study of 23 hours of video at a Kunming, China intersection that examined vehicle-involved interactions with powered two-wheelers (*14*). The authors suggest that present applications of PET or other time-proximity safety indicators that utilize fixed geographies for conflict measurement may be limited if mixed road users share smaller spaces and take evasive actions to avoid a collision (*14*).

As noted above, recent studies have evaluated pedestrian and bicyclist safety in smaller shared-use settings. Bietel et al (*7*) extracted 2,739 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 walking trajectories. However, the authors noted their effort to adapt PET measurements to smaller shared spaces may be insufficient alone for determining conflict severity in shared spaces. Nikiforiadis et al. (*15*) similarly introduced a new methodology for assessing pedestrian-bicyclist conflicts in shared spaces known as the hindrance concept, which involves defining an approximate one-meter radius around the two active travelers involved in an interaction. Meanwhile, the aforementioned study by Liang et al. (*8*) of active travelers in Shenzhen, used the Dutch Objective Conflict Technique for Operation and Research method to define and evaluate vulnerable road user conflicts. From this review, it is evident that the assessment of pedestrian and bicyclist safety conditions in shared-use settings has been explored but that (i) 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 (ii) previous vulnerable road user safety research has yet to explore the implications of low-speed automated delivery vehicles entering public spaces that have thus far largely been occupied by human travelers.

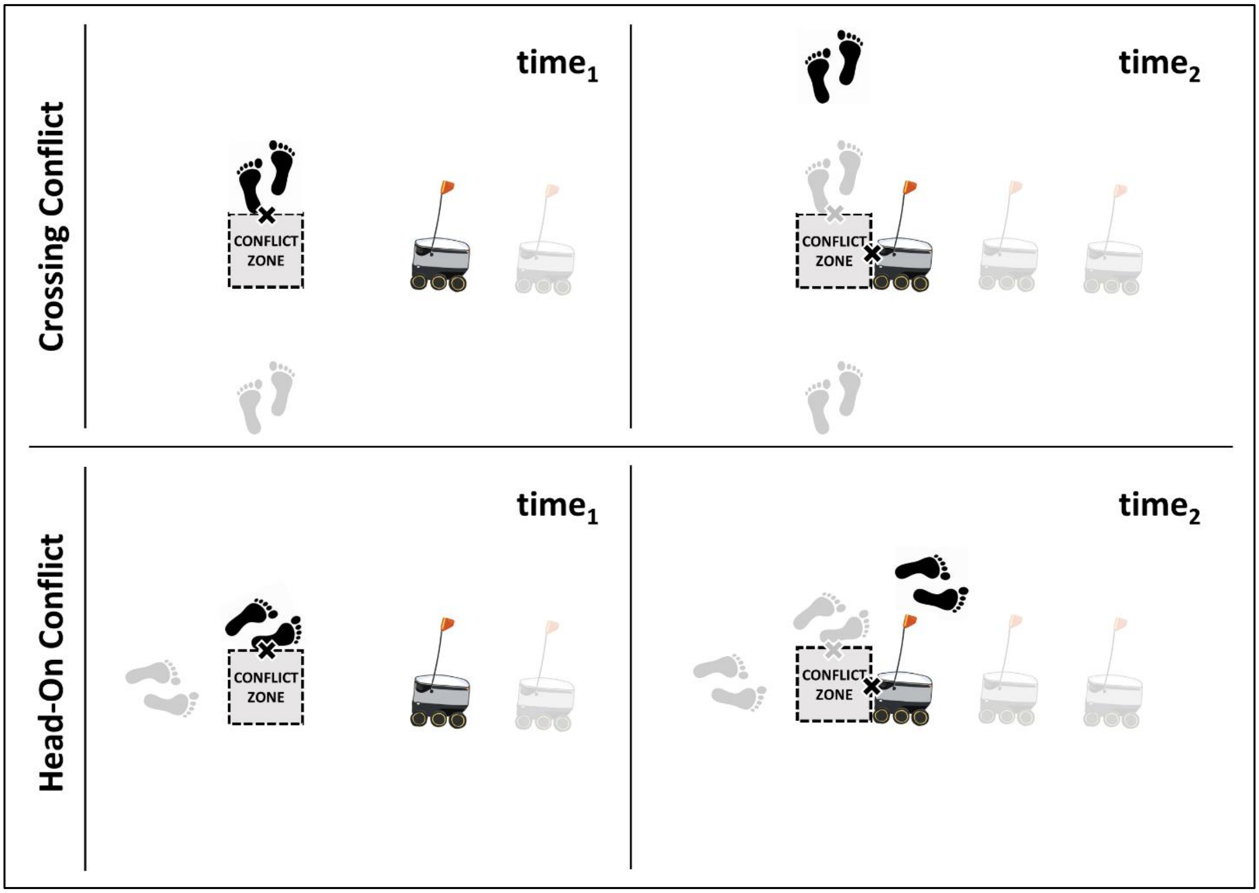
Methods

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). To measure the PET associated with an observed interaction, research team members (researchers) 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 researchers, using physical landmarks 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 in this study averaged 1,943 square feet (ranging from 503 to 3,550 square feet), with size variations attributed to the angle and height of stationary videorecorders 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 in bounding boxes, with an associated PET measurement identified for SADR-involved interactions. The PET measure was determined through a multi-step process in which researchers 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 (time1) and when the second user arrived to the conflict zone (time2) were recorded, with the PET of the given interaction then calculated as the difference between the two recorded timestamps (PET = time2 - time1). Figure 2 visualizes this sequence for two SADR-involved conflict types with a pedestrian. When viewing recorded interactions, researchers were able to pause, rewind, and fast forward videos, allowing for greater precision in interaction identification and PET measurement.

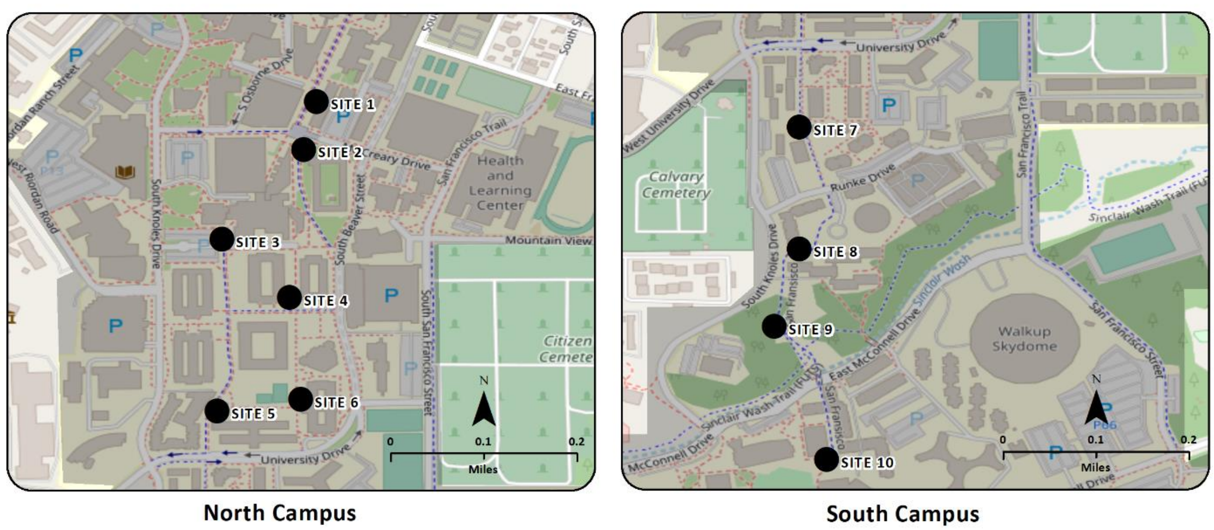
Figure 2. Illustration of PET measurement for two types of SADR-pedestrian conflicts



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, researchers selected ten sites along highly trafficked pathways in locations near significant SADR origins and destinations (e.g., student unions, residential halls). As shown in Figure 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 6pm at each site over five days in late September/early October 2021, under clear weather conditions and while in-person classes were held. This daily observation period coincides with Starship SADR delivery times, which may begin earlier or continue later depending on meal preparation location. To help 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-2:00pm, and 4:30-6:00pm. 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 hours of video across the sites was available for review and analysis.

Figure 3. Video collection sites on the north and south campus of NAU



After the final study observation period was determined, all field-collected recordings, which were parsed into 15-minute video clips, were reviewed by researchers in multiple phases. In the first phase of video review, each site was assigned to a researcher 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 researchers to identify SADR interactions with human pathway users and record the timestamps associated with each pathway user exiting or entering the conflict zone. Here, researchers 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 researchers who reviewed videos collected for a given site jointly 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 researchers, then the lower PET value was retained.
- If an interaction with a recorded PET value difference greater than one second was identified by two researchers, then the interaction was reviewed by both researchers 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 researcher, then the interaction was reviewed by both researchers until agreement on the PET value was reached (removing interactions with a PET value greater than five seconds from the final sample).

During the final video review phase, the two researchers 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, travel direction of the second pathway user in relation to the first pathway user, evasive actions taken by both pathway users, 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 sample, PET values for retained SADR-involved interactions were categorized into discrete severity levels. Based on prior research (*13;16*), observed interactions with a PET value of 1.5 seconds or less were categorized as a dangerous conflict, while SADR interactions with human pathway users that produced a PET value above 1.5 seconds 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.

Spatial description of 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 researchers 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 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 (*13*) 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 Equation 1 (*17*) and is an extension of a logistic regression model applied when the dependent variable is an ordered-response with more than two discrete levels:

$$P(y_i > j) = \frac{exp(X_i\beta' - \phi_j)}{1 + exp(X_i\beta' - \phi_j)} \qquad j = 1, 2, \dots, M-1 \qquad (1)$$

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.

Data and results

Description of 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 Figure 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 seconds. 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 Figure 4 46% and 39% of SADR interactions with pedestrians and bicyclists, respectively, were categorized as a normal interaction (level 0).

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

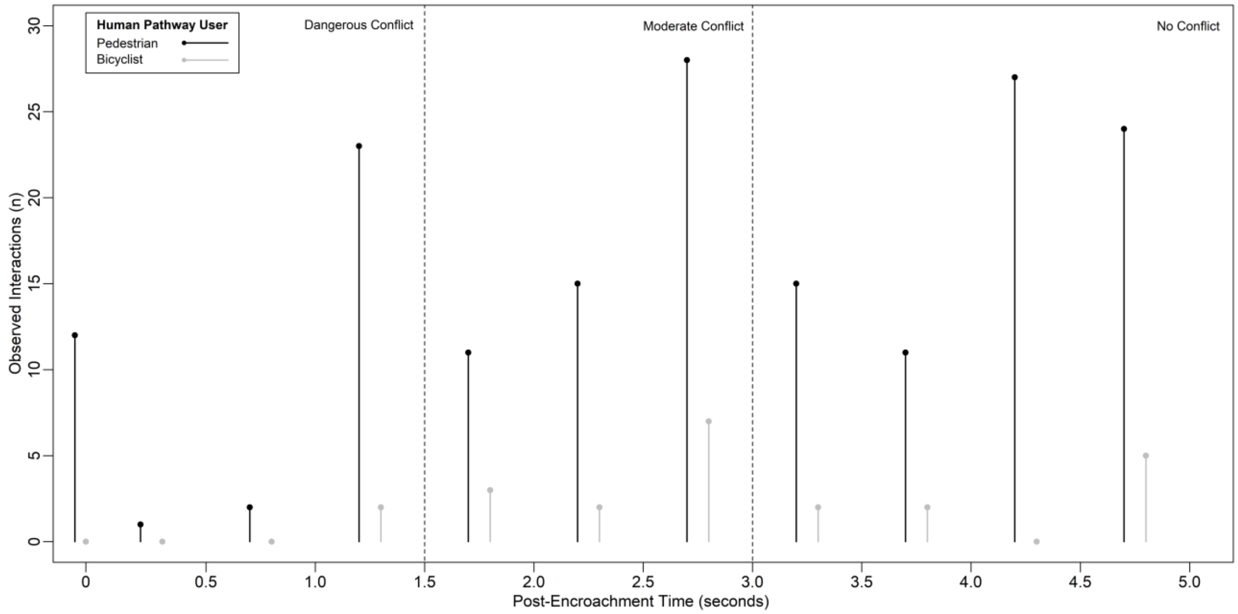


Table 1 provides a summary of the conflict- and site-level characteristics observed in the study sample of 201 SADR interactions with human pathway users (e.g., pedestrians, bicyclists) across the 10 sampling locations. On average, the PET for a recorded interaction was 2.79 seconds. Regarding the time 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 conflict area 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%).

Table 1. Descriptive statistics of observed SADR interactions and video collection sites

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-2:00pm)	0.68	0.47	0	1

Time of day: Evening (4:30pm-6:00pm)	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

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 SADR, 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 interactions 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.

Table 2. Evasive maneuvers of pedestrians and bicyclists in SADR interactions

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

Description of sites with 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 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.

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

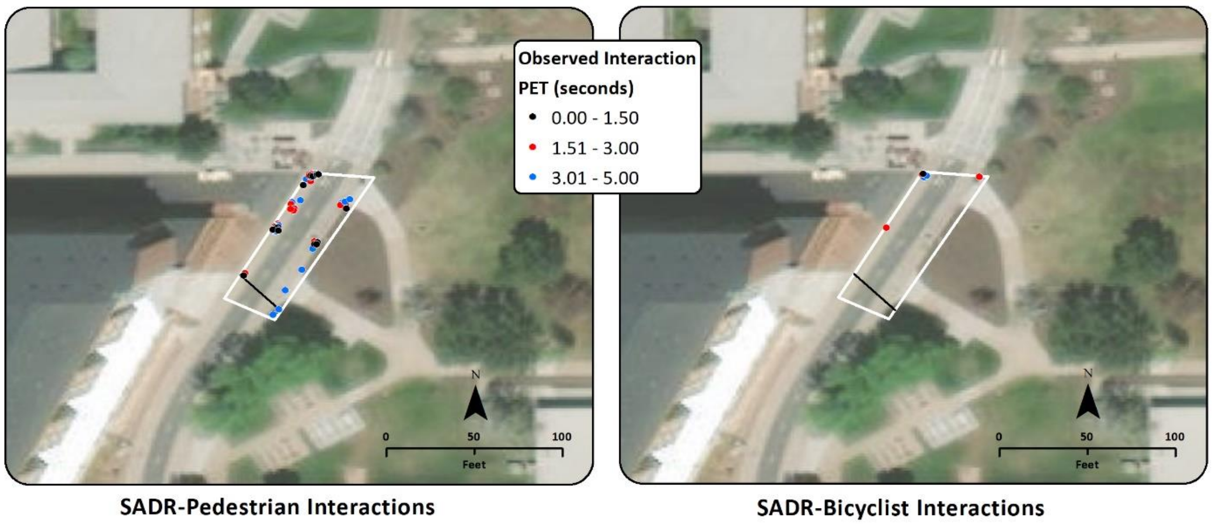
Site	Site Characteristics		15-min Exposure Counts					Observed SADR Interactions			
1	**Sidewalk width (ft)**	19.0		**SADR**	**Ped**	**Bike**	**Other**		**PET=0**	**PET=1**	**PET=2**
	Separated bike lane	Yes	**Mean**	2.2	243.7	26.3	17.5	**Ped**	8	1	2
	Lateral path barrier	No	**Min**	0	30	5	1	**Bike**	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

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 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 all campus sites. Sites 4 and 6 on north campus had fewer bicyclists, with one-hour exposure counts of 13 and 26 bicyclists, respectively. North campus sites 1 and 2, however, had the highest counts of 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 north of most campus dining options and on-campus residences, had the fewest recorded SADRs, while sites 8 and 9, which are located on a multiuse path connecting the south campus student union and several on-campus dormitories, had the highest count of SADRs.

Through a site-level investigation of SADR interactions with pedestrians, site 5 was found to have the most total interactions (n=55), with 16 interactions categorized as moderate conflicts and 14 interactions categorized as dangerous conflicts. Site 5 was also the location of one of the two observed SADR-bicyclist level 2 interactions. Figure 5 shows these locations of SADR-pedestrian and SADR-bicyclist interactions, by their PET category. 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 intersecting paths, with a set of dangerous conflicts observed at the two corners of a service road located to the west that intersects the 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.

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



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 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 also had the third highest number of SADR-bicyclist conflicts, which may be due to a mixing of all pathway users on a narrow shared-use facility. Meanwhile, site 3, which has a separated bike lane but two intersections, had the second highest number of SADR-bicyclist interactions (n=5). Of note, the two sites with the greatest bicyclist volumes (sites 1 and 2) had no recorded SADR-bicyclist interactions despite having comparable SADR volumes to site 3. Descriptively, this study finding and an absence of SADR-bicyclist interactions at site 7 may be related to the presence of separated bike lanes, wider sidewalks, and limited pathway intersections that when taken together signify ample space for overtaking actions and minimal opportunities for SADR and human pathway user routes to cross.

Modeled interactions of SADR interaction severity

Model results of SADR interactions with pedestrians, bicyclists, and 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. 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 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 sharing pathways with SADRs and offers evidence into the challenges of operating these new delivery technologies in a real-world 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 conflicts with human pathway users can be pursued by autonomous food delivery service providers and 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 when possible. SADR routes must also factor in the width of sidewalks to ensure that 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 walking. 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 shared-use path side that produces fewer bicyclist turning movements should be pursued when dedicated bike infrastructure is not present. Site-level examination should be given to locations along well-traversed routes where a bicyclist must transition from a dedicated facility (e.g., bike lane), where SADR use is unauthorized, to sidewalks shared by pedestrians as well as SADRs and an ever-increasing share of other human pathway users (e.g., e-scooters). Regarding the grouping of SADR-bicyclist interactions near bike parking facilities—visualized in Figure 5, 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 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.

This real-world analysis of SADR conflicts with pedestrians and bicyclists also underscored a need for future changes in the design of self-driving food delivery devices and the development of warning signs noting their presence. The identification of SADR-human pathway user interactions categorized as 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, design advancements to SADRs that improve their visual and audible detection by human pathway users should be considered. Presently, Starship robots produce a 'chirping' noise when close 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 faster than a pedestrian to make any required evasive maneuver. Accordingly, the instruction for SADRs to generate audible cues when traveling in 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 human pathway users to the increased potential for interaction with SADRs in these high-activity zones.

Although the development of 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 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 new micromobility options on already-crowded sidewalks. Accordingly, as SADR technology providers look to expand their markets beyond university 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.

Study 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 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 new 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 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 the PET-measured severity of SADR-involved interactions with active travelers tended to increase when an SADR crossed a human pathway user's intended trajectory, with a pedestrian or bicyclist often altering their path to avoid any collision. Findings suggest the safe introduction of SADRs onto urban pathways and curb spaces will be a challenge for practitioners that is likely to require innovative solutions in SADR route programming, public education, and infrastructure design.

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-human pathway user interactions, this study established an adapted PET metric that requires the creation of a site-level, static bounding box and a user-level, dynamic conflict area. 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 modeling. 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 comfort variation is likely to skew the sample toward interactions with a lower, non-zero PET and greater observed severity, 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.

Study 2: Reported Pedestrian and Bicyclist Comfort in Sharing Pathways with Sidewalk Autonomous Delivery Robots

Background

The growth and evolution of e-commerce, spurred by advancements in information and communication technology and public health conditions necessitating contactless delivery services to help mitigate Covid-19 transmission, has driven the demand for app-based automated delivery robots capable of transporting meals to customers in a safe and efficient manner (*18;19*). Though the real-world implementation of road autonomous delivery robots as a last-mile food or grocery delivery service remains in its pilot stage (*20*), the small-scale deployment of sidewalk autonomous delivery robots (SADR) has recently occurred in limited settings. In the United States, SADR deployment for food and drink deliveries has been primarily confined to university campuses and operated by Starship Technologies or Kiwibot, each of which have partnered with campus dining provider, Sodexo. Starship launched their autonomous delivery robots at George Mason University and Northern Arizona University (NAU) in early 2019 (*2*), while Kiwibot prototyped their low-speed automated delivery vehicle at the University of California, Berkeley one year prior (*21*). In Spring 2022, Kiwibot was operating its SADR food delivery service across 10 US college campuses (*22*) and Starship had SADR fleets traversing 18 campuses (*23*).

An expansion of automated delivery robot services across college campuses is largely motivated by the abundance of pedestrian paths and limited vehicular traffic found at these sites as well as a captive market of young, technology savvy adults with on-demand food delivery service experience (*24*). Meanwhile, US college students are also more likely to adopt sustainable travel modes (*25*) and the introduction of SADRs to shared-use paths designed for pedestrians and bicyclists that have witnessed an increase in micromobility-related conflicts (*26*) is likely to create new traffic safety concerns for active travelers on college campuses. However, to-date, limited evidence exists on how these emerging last-mile delivery services may be impacting pedestrian and bicyclist travel decisions or patterns in a real-world setting of SADR deployment despite the continued proliferation of these services across US college campuses and early efforts to expand into city neighborhoods.

In response, this study describes the design and administration of an original survey instrument to a campus population with experience adopting this new freight technology and traversing the shared-use pathways in which it operates. Specifically, this study seeks to (i) generate new evidence describing experiences with and future intentions to use automated food delivery services of a younger demographic who is more likely to be early adopters of new technologies and (ii) identify personal attributes and SADR-related experiences or intentions that are associated with self-reported comfort in sharing pathways with this new last-mile freight technology from the perspective of a pedestrian or bicyclist. In all, study findings are intended to offer new information for transportation planners and policymakers about the adoption of and safety concerns related to SADR fleet introduction and guidance on facility management strategies or design considerations that may facilitate a safe, future introduction of SADRs to more urban landscapes.

Literature review

The development of innovative last-mile food delivery technologies has become ever more important as the continued use of conventional car and driver methods (e.g., UberEats, DoorDash) to meet the growing demand for instantaneous meal deliveries has exacerbated urban traffic congestion. Autonomous delivery vehicles that use pathways shared by pedestrians, bicyclists, and new micromobility travelers have been introduced in limited settings as a possible future solution for more efficiently delivering food and drinks to technologically-inclined consumers. While some research has been conducted to assess the viability of SADRs as an effective food or parcel delivery service via an evaluation of existing legislation and technical capabilities that permit their operation or potential time cost savings that they may generate (*3*), any study of their performance in a real-world setting has been limited. Prior to the onset of the Covid-19 pandemic, last-mile package delivery research largely focused on identifying improvements in delivery route efficiency via computer-based automation (*19*). Yet, with the rise in public health concerns related to infectious disease transmission, interest in SADR-related studies has increased due to the intrinsic ability of robot delivery fleets to limit person-to-person contact (*20*) has led to a handful of recent studies investigating the willingness of certain markets to potentially adopt low-speed automated delivery services.

In an early study of SADRs as a last-mile delivery solution, Jennings and Figliozzi (*3*) examined the regulatory environment and technical capabilities of this new automated freight service to model their travel impacts in a generalized setting. The results from this study indicated that SADRs could potentially provide substantial cost and time savings under certain conditions and greatly reduce on-road travel per package delivery (*3*). In a second study, Boysen et al. (*27*) evaluated applications of truck-based SADR fleets in which a van transports smaller SADRs to a central depot where these devices are launched to autonomously deliver goods to nearby consumers, finding the use of decentralized robot depots may contribute to a more efficient parcel delivery process. Simoni et al. (*28*) also assessed the efficiency of truck-based SADR fleets to complete last-mile package deliveries by identifying a solution to a special case of the weighted interval scheduling problem that indicates robot-assisted delivery systems can be efficiently deployed in congested areas if the robots are fitted to hold multiple deliveries at once. Another hypothetical application of a popular vehicle routing problem was put forth by Chen et al. (*19*) to investigate the potential challenges and benefits of implementing self-driving delivery robots in cities, with study findings showing that their new heuristic algorithm could generate highly effective instances for managing demand from up to fifty consumers. By incorporating a set of SADR delivery route features such as sidewalk width, surface condition, presence of driveways and crosswalks, and route length, Corno and Savaresi (*29*) developed the Sidewalk Robot Feasibility Index (SRFI) as a new measure of SADR route feasibility along urban pathways.

While these reviewed studies centered on improving the efficiency and feasibility of SADR routes and systems, fewer studies have sought to identify consumer acceptance of automated delivery robots. Kasper and Abdelrahman (*18*) designed and administered a four-part survey instrument with questions using validated scales to investigate the user acceptance of automated delivery vehicles in Germany via an extension of the Unified Theory of Acceptance and Use of Technology. In analyzing the results of this online survey with 501 respondents, the authors revealed that price sensitivity was the strongest indicator of user acceptance but noted that most respondents were unfamiliar with this new technology and were solely reliant on the provided information sheet and their imagination (*18*). For a Portland, Oregon study of consumer attitudes toward autonomous delivery robot service adoption, Pani et al. (*20*) recruited a representative sample of 483 consumers using a four-part questionnaire eliciting information about their socioeconomic characteristics, shopping perceptions, mobility tools, and attitude changes around the Covid-19 pandemic. In this latter study, the authors identified six latent clusters that were then associated with a respondent's willingness to pay for autonomous delivery robot services, with findings suggesting that younger individuals and those with higher educational attainments and incomes were more likely to pay for contactless package deliveries (*20*).

Based on this reviewed literature, it is evident that research on SADRs or other automated delivery robot services has largely focused on improving the efficiency of their operation, with limited study of the demand consumers have for this technology. In fact, only a pair of studies were identified by the authors, which examined consumer preferences for SADRs and neither of those survey efforts were administered to a population with first-hand experience with their operation. Furthermore, there were no studies found by the authors that examined the safety impacts of operating SADRs on transportation facilities shared by human pathway users (e.g., pedestrians, bicyclists). This study's design and subsequent administration of an original survey instrument aimed at revealing SADR adoption patterns and identifying the traffic safety concerns attributed to their deployment in a real-world setting helps to address recognized gaps in this new research area and offer needed guidance to transportation planners and policymakers on the topic.

Methods

Survey instrument and administration

The Perceptions of Autonomous Robots for Deliveries (PAR-D) survey instrument (Appendix A) was designed to identify the perceptions of and experiences with SADRs shared by NAU students, faculty, and staff; a community with three years of real-world knowledge pertaining to the adoption of and interaction with SADR services. The design of the tablet-based PAR-D survey instrument in Qualtrics software was reviewed and approved by the Institutional Review Board of NAU (Project #1891635-1). The survey instrument consisted of three components and 20 questions and was designed to take a participant less than five minutes to complete. In the first section (Survey Participant Information), survey participants were asked to answer questions regarding their sociodemographic and economic background and general travel behaviors. Responses to these questions, which provided information on a survey respondent's self-reported age, gender, race or ethnicity, income, employment status, and educational attainment as well as information regarding their residential location and common travel modes, were collected to help illustrate the characteristics of this study's sample associated with recent and future SADR utilization.

The survey instrument's second section (Autonomous Delivery Vehicles) sought to collect information on the reported experiences of participants with SADRs operating on the NAU campus, their perceptions regarding comfort for sharing pathways with SADRs as a pedestrian or bicyclist, their intentions of adopting autonomous food delivery services in the future, and whether autonomous food delivery vehicles would operate best on pathways exclusive to pedestrians and bicyclists or roadways with motorists. Responses to these last three items were recorded using a five-point Likert scale ranging from least to most agreement. The aforementioned question on SADR use employed seven ordered categories that ranged from 'never' to 'one or more times per day', while two questions on comfort in sharing pathways with SADRs as a pedestrian or bicyclist were paired with five-point Likert scales that ranged from ‘very uncomfortable’ to ‘very comfortable’, with an option to state they ‘don’t know’ or in the case of the latter mode, ‘don’t ride a bicycle’.

The final section of the PAR-D survey instrument presented a stated choice experiment in which participants were presented with four five-second field-recorded videos showing a head-on conflict with an SADR from the perspective of a pedestrian or bicyclist. Two videos were shown for each active traveler type, with the pedestrian or bicyclist taking a lateral evasive maneuver within two differing times before a possible SADR-involved collision. The four videos were recorded in a controlled setting on NAU’s campus, with the evasive action of the pedestrian or bicyclist made at approximately one or three seconds before an SADR collision would occur. The decision to record videos with these evasive action times was informed by applying a surrogate safety measure, post-encroachment time (PET), which has been used recently in the study of active traveler safety in public shared spaces (*7*). PET is defined as the time elapsed from the moment when a vehicle (or other pathway user) departs a potential collision site to the moment of arrival at the potential collision site by a conflicting vehicle or other pathway user (*6*), with a smaller PET value reflecting a more-severe conflict and a value of zero seconds indicating a collision. The recording of videos in this study’s choice experiment with PET values of approximately one and three seconds, representing a dangerous and moderate SADR-involved conflict, respectively. Figure 6 provides screen shots from two of the videos showing dangerous conflicts between an SADR and pedestrian (left image) and SADR and bicyclist (right image). After viewing each video, survey participants, who were given the ability to replay the field recording, were asked to indicate their comfort in sharing the pathway with an autonomous delivery vehicle by using an ordered five-point scale: Very uncomfortable, uncomfortable, neutral, comfortable, or very comfortable.

Figure 6. Video screen shot of SADR conflicts in stated choice experiment with pedestrian (left) and bicyclist (right)

For this study, the PAR-D survey instrument was administered to a sampling population of NAU students, faculty, and staff at the two campus unions where Starship SADRs regularly depart to offer food and drink deliveries to on-campus buildings and residences. Intercept survey responses were collected by a team of three survey administrators during two weeks in April 2022, when in-person classes were in session. Each survey administrator was equipped with a portable tablet device connected to Wi-Fi services, which they presented to a prospective survey participant with a brief prompt inquiring about their willingness to take a five-minute survey about their individual perceptions of Starship robots. In total, 526 survey responses were collected inside both the University Union on north campus and the du Bois Center on south campus, with four responses removed from the final study sample due to incompleteness.

Statistical analysis

Using this primary data set, a statistical analysis was conducted to understand how information collected on a survey respondent's socioeconomic background, travel behaviors, and experiences and perceptions regarding SADR utilization and pathway interactions relates to their reported comfort in sharing pathways with SADRs as a pedestrian or bicyclist. The outcome variables for this analysis are the responses received to the four stated choice experiments, as a function of variables constructed from responses to questions in the PAR-D survey instrument's first two sections. Provided the ordered nature of the outcome variables, an ordered logistic regression analysis was pursued. However, the relatively small sample size of this study (n=522) and the likely prospect for existing differences in mode-specific responses related to comfort (i.e., walking is more common than bicycling by the campus population) necessitated a review of the ordered logistic regression's assumption of proportional odds. In addition to ensuring that a balanced distribution of survey responses was tallied for each response category, any aggregation of the original responses to the stated choice experiments needed to be identical across the two SADR-pedestrian and SADR-bicyclist questions. As a result, the outcome variable for the two models of pedestrian-related comfort in evading a possible SADR conflict recorded PET values of one and three seconds, respectively, were aggregated to four levels, where: 0 = Very uncomfortable or uncomfortable, 1 = Neutral, 2 = Comfortable, and 3 = Very comfortable. A further aggregation of the original response categories was made for outcome variables in the two models of bicyclist-related comfort in evading a possible SADR conflict due to limited responses of 'comfortable' or 'very comfortable', resulting in the following three levels: 0 = Very uncomfortable or uncomfortable, 1 = Neutral, 2 = Comfortable or very comfortable.

Proceeding with these adjusted responses, the four ordered logistic models specified in this study can be expressed in Equation 2 (*17*), which is an extension of a logistic regression model applied when a dependent variable is an ordered-response with two or more discrete levels:

$$P(y_i > j) = \frac{exp(X_i\beta' - \phi_j)}{1 + exp(X_i\beta' - \phi_j)} \qquad j = 1, 2, \ldots, M - 1 \tag{2}$$

where j is the self-reported comfort level, X_i is a vector of revealed survey respondent attributes, β is a vector of estimated parameters, φ_j are the breakpoints associated with the comfort level thresholds, and M is the number of categories of the ordered-response variables for SADR-pedestrian and SADR-bicyclist conflicts after employing the above aggregation process.

Each of the four ordered logistic regression models constructed for this analysis of active traveler comfort in evading an approaching SADR on a shared-use pathway was specified via the following process. Initially, unadjusted Spearman's Rank correlation coefficients were calculated for each survey respondent attribute and SADR-related responses to items in the survey instrument's second section. Predictors with a marginally significant association ($p<0.10$) were identified and added to a full model specification. Then, beginning with the full model specification, a backwards elimination process was performed to remove non-significant predictors from a final model specification. This iterative process of independent variable removal was performed by dropping the predictor with the highest, non-significant p-value ($p>0.10$) until a final specification was reached where all remaining independent variables were significant predictors of the ordered outcome variable.

Data and results

Survey respondent profile

In all, 522 valid responses were received from the two-week administration of the PAR-D survey on NAU's campus. Table 5 provides a summary of the sociodemographic and economic characteristics of the final study sample in addition to information on modes adopted for travel to and around the university campus. Nearly three out of four survey respondents stated that their residence was one of the on-campus student housing options. Among the survey respondents who noted residing off-campus (n=131), approximately two-fifths (41%) of respondents noted a car was their most common means of traveling to NAU. In turn, about one quarter (24%) of off-campus survey respondents stated that they commonly walked to campus, with the remainder of off-campus respondents either primarily riding public transit (20%) or cycling (10%) when traveling to campus. While at campus, a vast majority of all survey respondents noted that walking (85%) was one way they traveled around campus, with about one half (48%) of students traversed campus on a bus. Less than one third (32%) of survey respondents noted that they traveled via car around campus, while only 16% of survey respondents noted riding their private bicycle or one provided by the university's shared Yellow Bike Program around campus.

Table 5. Descriptive statistics of PAR-D survey respondents

Variable	Count (n)	Share (%)
Residence: On-campus	391	74.90
Residence: Off-campus	131	25.10
Gender: Male	226	43.29
Gender: Female	272	52.11
Gender: Non-binary or self-describe	24	4.60
Age: 18-24 years old	503	96.36
Age: 25-34 years old	16	3.10
Age: 35 years old or more	3	0.58
Education: High school or less	59	11.30
Education: Bachelors or some college	460	88.12
Education: Masters of PhD	3	0.58
Race/Ethnicity: American Indian or Alaska Native	9	1.73
Race/Ethnicity: Asian	26	5.01
Race/Ethnicity: Black/African American	13	2.50

Race/Ethnicity: Hispanic/Latinx	65	12.52
Race/Ethnicity: Multiple races or ethnicities	47	9.06
Race/Ethnicity: Native Hawaiian or Pacific Islander	6	1.16
Race/Ethnicity: White, Non-Hispanic	353	68.02
Personal Income: Less than $15,000	435	90.06
Personal Income: $15,000-$34,999	42	8.70
Personal Income: $35,000-$49,999	2	0.41
Personal Income: $50,000 or more	4	0.83
Work status: Part-time student	13	2.58
Work status: Full-time student	388	75.19
Work status: Part-time employment	186	36.05
Work status: Full-time employment	18	3.49
Travel mode: To campus (car)	54	54.55
Travel mode: To campus (walk)	32	32.32
Travel mode: To campus (bike)	13	13.13
Travel mode: Around campus (car)	165	31.67
Travel mode: Around campus (walk)	444	85.22
Travel mode: Around campus (bike)	81	15.55

Regarding the sociodemographic and economic attributes of the study sample, most survey respondents identified their gender as female (52%), with the remainder of survey respondents to this question stating they were male (43%) or non-binary (5%). In terms of survey respondents' race and ethnicity, about two thirds (68%) of survey respondents in the final study sample identified as White, Non-Hispanic, with 13% of respondents identifying as Hispanic or Latinx and 9% describing themselves as multiracial or multiethnic. To be expected when surveying a university population, the age distribution across the study sample was heavily skewed and not representative of a general population, with 96% of survey respondents between 18 and 24 years of age. Accordingly, the educational attainment response for the study sample almost entirely fell into the categories encompassing a high school diploma or some college (99%). Not shown in Table 1, of the 401 survey respondents who were enrolled as a part- or full-time student, about one half (48%) of those students were Freshman. This overrepresentation in the sample is attributable to a decision to administer the survey in student unions with assorted meal options and the requirement of the university for all first-year students living on-campus to purchase an annual meal plan. While many survey respondents were currently students at NAU, 39% of respondents stated they were also part- or full-time workers. Though, the most popular personal income cohort found in the study sample reflected an annual income less than $15,000.

The PAR-D survey instrument's second component sought to identify experiences of survey respondents with SADRs in a real-world setting and to understand their perspectives regarding a potential future wide-scale deployment of low-speed automated freight vehicles. Table 6 summarizes the results from this part of the survey instrument. When asked about the frequency at which survey respondents use Starship robot delivery services to order meals or drinks, which cost $1.99 per delivery, about three out of four (76%) survey respondents stated they had adopted this delivery service at least once in the past. Of those 393 respondents with experience using Starship delivery services, there was a well-balanced distribution of individuals who had used the service less than once per month over the past year (49%) and those who adopt this service at least twice per month (51%). Moreover, almost one quarter (23%) of sampled individuals who had adopted Starship delivery services in the past stated they utilize this service once a week or more. Meanwhile, 36% of survey respondents agreed (level 4) or strongly agreed (level 5) with a five-point Likert scale statement about the future adoption of autonomous delivery vehicles as a food or grocery delivery option, with disagreement (level 2) or strong disagreement (level 1) from 34% of respondents and a neutral (level 3) response (29%) from the remainder of respondents.

Table 6. Descriptive statistics of PAR-D survey responses regarding SADRs

Survey Instrument Item and Response	Count (n)	Share (%)
How often do you use Starship robot delivery services to order food or drinks?		
Never	126	24.14
Very rarely (one time per year or less)	87	16.67
Rarely (one time per month or less)	108	20.69
Occasionally (two or three times per month)	109	20.88
Frequently (one time per week)	51	9.77
Very frequently (two or more times per week)	30	5.74
Always (one or more times per day)	11	2.11
As a PEDESTRIAN or a BICYCLIST, have you altered your intended path because of an interaction with an autonomous Starship robot delivery service?		
Yes	371	71.49
No	132	25.43
Don't know	16	3.08
As a PEDESTRIAN, what is your comfort in sharing pathways with autonomous robot delivery services?		
Very uncomfortable	36	6.90
Uncomfortable	25	4.79
Neutral	141	27.00
Comfortable	169	32.38
Very comfortable	150	28.74

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Don't know	1	0.19
As a BICYCLIST, what is your comfort in sharing pathways with autonomous robot delivery services?		
Very uncomfortable	28	5.36
Uncomfortable	57	10.92
Neutral	108	20.69
Comfortable	44	8.43
Very comfortable	31	5.94
Don't know or don't ride a bicycle	254	48.66
I intend to use autonomous delivery vehicles as a food or grocery delivery option.		
1 (Least agreement)	100	19.16
2	80	15.32
3	152	29.12
4	127	24.33
5 (Most agreement)	63	12.07
Autonomous delivery vehicles will work well if sharing pathways with only pedestrians and bicyclists.		
1 (Least agreement)	28	5.38
2	84	16.12
3	195	37.43
4	131	25.14
5 (Most agreement)	83	15.93
Autonomous delivery vehicles will work well if sharing roadways with only motorists.		
1 (Least agreement)	164	31.48
2	175	33.59
3	123	23.61
4	33	6.33
5 (Most agreement)	26	4.99

Comfort in sharing pathways with SADRs

Administration of the PAR-D instrument also provided insights into the comfort that survey respondents expressed for sharing pathways with SADRs as active travelers on NAU's campus. About one half of survey respondents stated they were either comfortable (32%) or very comfortable (28%) with sharing pathways with SADRs, with 11% expressing that they were either uncomfortable or very uncomfortable. Over three quarters (76%) of female survey respondents noted that they were comfortable or very comfortable with sharing pathways with SADRs, while a fewer percentage (61%) of male survey respondents stated a similar level of comfort in sharing pathways with autonomous robot delivery services as a pedestrian (Table 7). In terms of travel modes, 63% of survey respondents who primarily walk to campus and 60% of survey respondents who walk around campus stated that they were comfortable or very comfortable in sharing pathways with SADRs as a pedestrian. While only a fraction (13%) of survey respondents rides a bicycle to campus, 27% of those respondents who ride a bicycle expressed that they were comfortable or very comfortable in sharing pathways with SADRs. In contrast to the reported comfort in sharing pathways with SADRs as a pedestrian, only 32% of female survey respondents noted that they were comfortable or very comfortable with sharing pathways with SADRs as a bicyclist, while about one quarter (24%) of male survey respondents stated a similar level of comfort. Furthermore, more than two out of five (41%) survey respondents who ride a bicycle around campus reported being uncomfortable or very uncomfortable with sharing pathways with SADRs as a bicyclist.

Table 7. Reported comfort sharing pathways with SADRs by select variables

What is your comfort sharing pathways with autonomous robot delivery services?	**As a PEDESTRIAN**					**As a BICYCLIST**				
Variable	**VU**	**U**	**N**	**C**	**VC**	**VU**	**U**	**N**	**C**	**VC**
Gender: Male	13	11	62	85	55	14	40	55	23	11
Gender: Female	23	14	73	78	92	14	17	48	19	19
Gender: Non-binary/self-describe	0	0	6	6	3	0	0	5	2	1
Travel mode: To campus (car)	4	2	12	18	18	1	3	14	3	2
Travel mode: To campus (walk)	3	1	8	7	13	0	3	6	3	6
Travel mode: To campus (bike)	0	0	6	4	3	1	6	5	1	0
Travel mode: Around campus (car)	17	10	37	49	52	10	8	29	17	9
Travel mode: Around campus (walk)	29	21	125	143	125	24	47	87	34	23
Travel mode: Around campus (bike)	3	2	25	32	19	7	26	26	16	6
As a PEDESTRIAN or a BICYCLIST, have you altered your intended path because of an interaction with an autonomous Starship robot delivery service?										
Response	**VU**	**U**	**N**	**C**	**VC**	**VU**	**U**	**N**	**C**	**VC**
Yes	21	21	116	123	89	20	51	83	26	14
No	14	3	19	36	60	7	4	22	15	17
Don't know	1	1	5	8	1	1	1	1	3	0
Autonomous delivery vehicles will work well if sharing pathways with only pedestrians and bicyclists.										
Response	**VU**	**U**	**N**	**C**	**VC**	**VU**	**U**	**N**	**C**	**VC**

1 (Least agreement)	7	6	9	3	3	6	5	4	1	2
2	3	9	38	25	9	7	14	17	3	3
3	12	4	56	79	44	7	26	51	14	7
4	7	2	28	43	50	6	8	20	16	5
5 (Most agreement)	7	4	9	19	44	2	4	16	10	14

Autonomous delivery vehicles will work well if sharing roadways with only motorists.

Response	VU	U	N	C	VC	VU	U	N	C	VC
1 (Least agreement)	16	11	44	41	52	14	21	27	6	10
2	6	6	59	67	36	5	26	37	17	8
3	7	6	32	41	37	6	8	29	10	9
4	3	2	3	12	13	1	0	8	8	1
5 (Most agreement)	4	0	3	7	12	2	2	5	3	3

The last pair of questions in the survey instrument's second component applied the previously described five-point Likert scale to understand what types of transportation facilities would be most suitable for the operation of autonomous delivery vehicles. Again, about two out of five (41%) survey respondent believed that autonomous delivery vehicles will work well if sharing pathways with only pedestrians and bicyclists, which is currently the circumstance at NAU's main campus, while only 11% of survey respondents agreed (level 4 or level 5) with the statement that autonomous delivery vehicles would work well if sharing roadways with only motorists. Looking at respondents who noted being comfortable or very comfortable in sharing pathways with SADRs as a pedestrian, about one half (49%) of those survey respondents agreed (level 4) or strongly agreed (level 5) that autonomous delivery vehicles will work well if sharing pathways with only pedestrians and bicyclists. Moreover, just 17% of survey respondents who reported being comfortable or very comfortable in sharing pathways with SADRs as a bicyclist agreed or strongly agreed that autonomous delivery vehicles will work well if sharing pathways with only pedestrians and bicyclists. However, few survey respondents who stated they were either very uncomfortable or uncomfortable in sharing pathways with SADRS as a pedestrian (15%) or bicyclist (6%) agreed (level 4) or strongly agreed (level 5) that autonomous delivery vehicles would work well if sharing pathways with only motorists. Taken together, the descriptive results highlighted in Table 3 appear to illustrate that pedestrians tended to be comfortable sharing facilities with SADRs but that those who were comfortable are split on how well SADRs operate on pathways shared with pedestrians and bicyclists. Bicyclists, in turn, have less comfort sharing pathways with these low-speed autonomous delivery vehicles but do not necessarily believe that this new technology will operate better in traffic with only motorists (e.g., roadways) than on facilities already shared by pedestrians and bicyclists.

Results from the final component of the PAR-D survey instrument, which was a choice experiment where survey participants were shown four five-second videos of an SADR interaction from the perspective of a pedestrian or bicyclist, were then analyzed by specifying four ordered logit models. The outcome in each model was the self-reported comfort that a survey respondent would have for sharing a pathway with an SADR after viewing each video. Figure 7 shows the distribution of responses for participants who viewed the two videos from the perspective of a pedestrian making a lateral evasive maneuver out of the path of an oncoming SADR within one and three seconds, respectively, of a potential collision. Overall, the results illustrate that survey respondents tended to be comfortable in either scenario but were more likely to report a neutral comfort level after viewing the video with the lower evasive maneuver time. The distribution of responses following the viewing of the two videos from the perspective of a bicyclist who was avoiding a potential collision with an SADR are shown in Figure 8. The reported comfort levels were lower for the bicyclist than the pedestrian, with a neutral response being the most popular selection for each evasive maneuver time and respondents more likely to report being uncomfortable rather than very comfortable or comfortable after viewing the video of an evasive action made by the bicyclist one second prior to a potential SADR-involved collision.

Figure 7. Reported pedestrian comfort in sharing a pathway with an SADR from two stated choice experiments

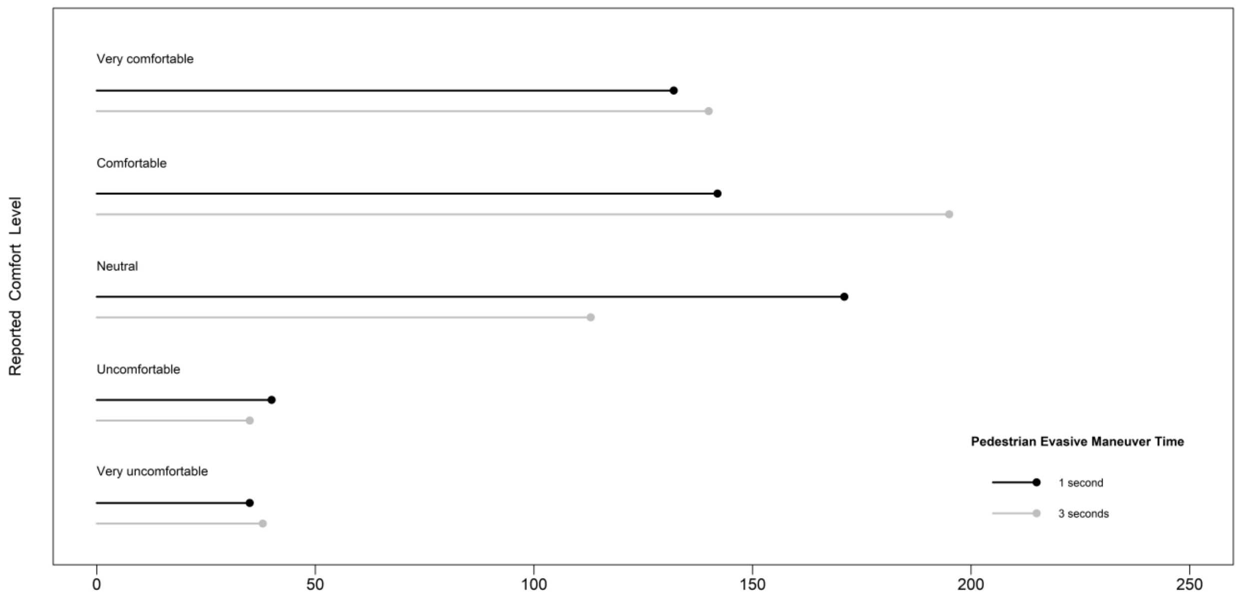

Figure 8. Reported bicyclist comfort in sharing a pathway with an SADR from two stated choice experiments

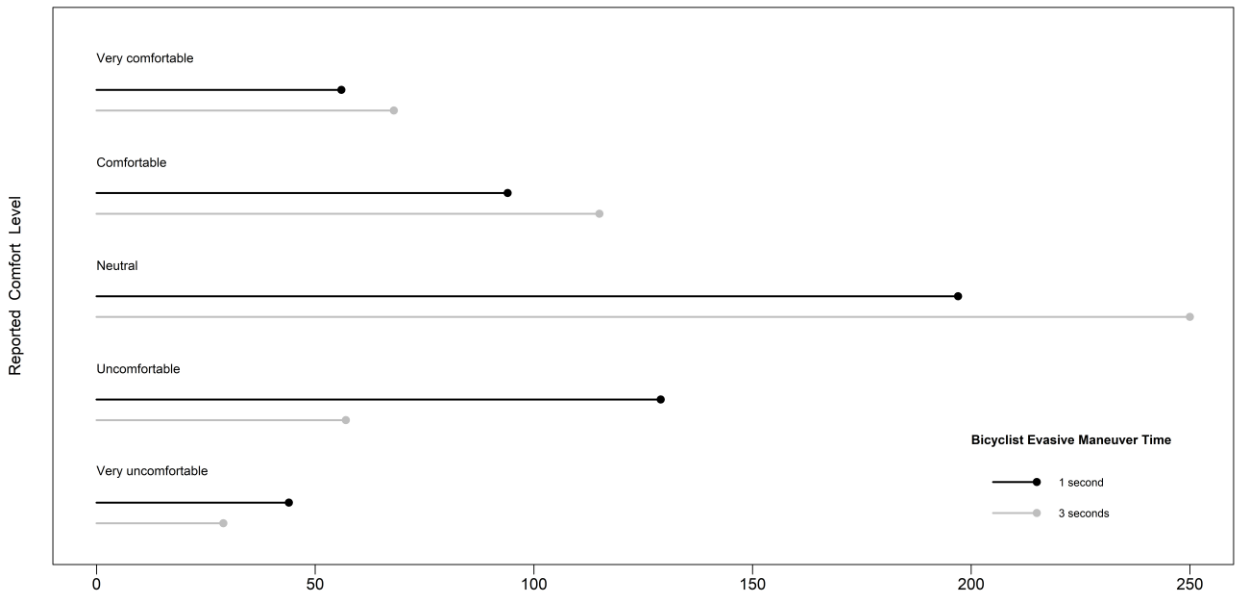

Table 8 summarizes the results of models in which the reported comfort for making an evasive maneuver one or three seconds in advance of a pedestrian possibly colliding with an oncoming SADR was a function of responses to the first and second components of the survey instrument. Investigating the results of the model with an estimated PET value of three seconds, survey respondents who revealed being either very uncomfortable or uncomfortable in sharing pathways with SADRs as a pedestrian were less likely to be comfortable having to make the evasive maneuver portrayed in the choice experiment's video, whereas survey respondents who expressed some level of comfort in sharing pathways with SADRS tended to be comfortable with making an evasive maneuver that was three seconds before a potential SADR-involved collision. Survey respondents who were more likely to agree with statements about their future intention to adopt autonomous food delivery vehicles or note these services would only operative effectively if they were to share pathways exclusive to pedestrians and bicyclists were also found to be more comfortable with the three-second evasive action made by the pedestrian. Each of these variables was also a significant predictor in the model of an SADR-pedestrian interaction with an estimated PET value of one second, with no change in their direction of association. In this second model, an individual who reported being very comfortable or comfortable with sharing pathways with SADRs as a bicyclist was also comfortable with the one-second evasive action taken by the pedestrian. Furthermore, respondents who revealed that they presently use Starship robot delivery services at least twice per month appeared to be more comfortable as a pedestrian sharing a pathway with an SADR in which they would need to change their walking path one second prior to a potential collision. Yet, survey respondents who stated that they had altered their trajectory in the past as a pedestrian or bicyclist in order to avoid a collision with an SADR were less likely to be comfortable with the one-second evasive maneuver made by the pedestrian in the second video. A model result which may reflect discomfort experienced by a survey respondent from a previous near-miss or collision with an SADR operating in a real-world setting and concern over a similar future occurrence.

Table 8. Ordered logit model results for pedestrian conflict with an SADR

Outcome:	PET = ~3 seconds				PET = ~1 second			
Variable	**Beta**	**SE**	**CI: 5%**	**CI: 95%**	**Beta**	**SE**	**CI: 5%**	**CI: 95%**
SADR-related Responses								
Current SADR Utilization								
Occasionally or more					0.32	0.18	0.02	0.62
Altered Path as Pedestrian or Bicyclist					-0.51	0.19	-0.81	-0.20
Share Path with SADR as Pedestrian								
Uncomfortable or Very Uncomfortable	-0.96	0.32	-1.50	-0.43	-1.15	0.33	-1.70	-0.61
Comfortable or Very Comfortable	1.36	0.20	1.04	1.69	1.39	0.21	1.06	1.73
Share Path with SADR as Bicyclist								
Comfortable or Very Comfortable					0.41	0.25	<0.01	0.81
Future Intention of SADR Utilization	0.27	0.07	0.15	0.38	0.17	0.07	0.05	0.29
SADR Paths with Pedestrians and Bicyclists	0.27	0.08	0.13	0.41	0.35	0.09	0.21	0.50
Intercepts								
Threshold: 0 and 1	0.18	0.31			-0.08	0.38		
Threshold: 1 and 2	1.68	0.31			2.14	0.38		
Threshold: 2 and 3	3.68	0.35			3.70	0.41		
Model Summary								
Number of observations				518				518
Log likelihood				-611.19				-595.02
Log likelihood (constants only)				-687.40				-697.38
Akaike information criterion				1236.38				1210.04

Table 9, in turn, summarizes the estimation of two ordered logit models of a survey respondent's level of comfort with having to take an evasive action to avoid a collision with an SADR as a bicyclist, as depicted in separate videos with PET values of three and one second, respectively. For the model of the less-severe SADR-bicyclist interaction, survey respondents who were very uncomfortable or uncomfortable sharing a pathway with an SADR as either a bicyclist or pedestrian were less likely to be comfortable with watching a bicyclist take an evasive maneuver three seconds prior to a possible SADR-involved collision. Meanwhile, survey respondents who expressed comfort in sharing pathways with

SADRs as a bicyclist or pedestrian were more likely to be comfortable with the recorded SADR-involved conflict from a bicyclist's perspective. Individuals who recorded a greater level of agreement with the survey instrument's statements regarding their intention to adopt autonomous food delivery services in the future and their belief that autonomous delivery vehicles would operate well if sharing pathways with only pedestrians and bicyclists or with only motorists (mutually exclusive questions) in the future were positively related to their comfort level after viewing the bicyclist-SADR conflict video with a PET value of approximately three seconds. However, those survey respondents who reported altering their paths in the past due to the presence of an SADR on their pathway were not as comfortable with the less-severe of the two bicyclist-SADR conflicts depicted in the choice experiment than their counterparts who did not report encountering this circumstance previously.

Table 9. Ordered logit model results for bicyclist conflict with an SADR

Outcome:	**PET = ~3 seconds**				**PET = ~1 second**			
Variable	**Beta**	**SE**	**CI: 5%**	**CI: 95%**	**Beta**	**SE**	**CI: 5%**	**CI: 95%**
Respondent Characteristics								
Travel mode: Around campus (car)					0.58	0.20	0.25	0.90
Travel mode: Around campus (bike)					-0.47	0.28	-0.93	-0.01
SADR-related Responses								
Current SADR Utilization								
Rarely or Very Rarely					-0.45	0.19	-0.76	-0.14
Altered Path as Pedestrian or Bicyclist	-0.48	0.21	-0.83	-0.13	-0.76	0.21	-1.10	-0.42
Share Path with SADR as Pedestrian								
Uncomfortable or Very Uncomfortable	-0.90	0.32	-1.43	-0.37	-0.63	0.31	-1.14	-0.13
Comfortable or Very Comfortable	0.59	0.22	0.23	0.96				
Share Path with SADR as Bicyclist								
Uncomfortable or Very Uncomfortable	-0.93	0.26	-1.36	-0.50	-1.16	0.29	-1.65	-0.69
Comfortable or Very Comfortable	1.91	0.34	1.37	2.50	2.19	0.33	1.67	2.75
Future Intention of SADR Utilization	0.16	0.08	0.03	0.29				
SADR Paths with Pedestrians and Bicyclists	0.23	0.10	0.07	0.38	0.39	0.09	0.24	0.54
SADR Paths with Motorists	0.30	0.09	0.15	0.45	0.36	0.09	0.22	0.51
Intercepts								
Threshold: 0 and 1	-0.17	0.44			0.56	0.41		
Threshold: 1 and 2	2.74	0.46			2.78	0.43		

Model Summary		
Number of observations	518	518
Log likelihood	-426.64	-447.74
Log likelihood (constants only)	-527.23	-565.87
Akaike information criterion	873.29	917.48

As for the model results pertaining to a respondent's comfort with the more-severe bicyclist-SADR conflict, an individual was also less likely to be comfortable with the recorded one-second PET interaction if they had previously altered their walking or bicycling trajectory because of an SADR traveling on their pathway. Similarly, respondents who expressed being uncomfortable or very uncomfortable sharing pathways with SADRs as a pedestrian or bicyclist were less comfortable with the evasive action taken by the bicyclist in the one-second video to avoid an SADR collision. A negative association with this outcome variable was also estimated in relation to current SADR utilization, with respondents who have only used autonomous food delivery services rarely or very rarely in the previous year reporting less comfort having to take an evasive action within one-second of a possible SADR-bicyclist collision. In contrast, respondents who were found to be either comfortable or very comfortable sharing pathways with SADRs as a bicyclist were comfortable with the one-second evasive action taken by the bicyclist in the second video. Aligned with model results of the prior video showing a PET value of three seconds, respondents in greater agreement regarding the potential for automated delivery services in the future to work well on facilities with only pedestrians and bicyclists or only motorists also tended to report greater comfort with the more-severe interaction of an SADR approaching an evading bicyclist. Interestingly, however, individuals who bicycle around campus as a means of travel were less likely to be comfortable with the video of a bicyclist evading the trajectory of an oncoming SADR one-second prior to a possible collision, while the opposite relationship held true for survey respondents who reported traveling around campus in a car.

Study conclusions

This study has sought to help advance a nascent evidence base on the adoption of emerging autonomous delivery robots and the possible safety impacts for pathway users who share their transportation facilities. While a handful of studies have investigated the acceptance of automated last-mile delivery vehicles for different market segments, there has been less examination into the adoption of these services in settings where autonomous delivery robot fleets have been deployed. The design of an original survey instrument and its administration in this study to a younger, university population who may be more likely to adopt these services in the future (*20*) offered insights on the experiences and future intentions to adopt SADR services for a market segment with the real-world experience of a small-scale deployment of this last-mile freight delivery technology.

Across this study's sample of mostly university students, about three quarters (76%) of all survey respondents had adopted SADRs for food deliveries in the past year, with nearly one quarter of (23%) this subset of respondents stating they received SADR food deliveries at least once per week. These findings revealed a proclivity for this younger demographic to adopt SADRs and helped to substantiate the growing popularity of an autonomous delivery robot service that started only three years before this study's data collection effort. Moreover, the prospect of these last-mile food delivery services to retain their successful market penetration appear to be optimistic given that roughly two-thirds (64%) of all survey respondents were either in agreement or neutral when asked if they intend to adopt autonomous delivery vehicles as a food or grocery delivery option if they become more common in public places in five years. Recognizing the survey was administered at dining locations, which may have resulted in some undercounting of high-activity SADR adopters who prefer at-residence food deliveries, these study findings illuminate a potential for the demand of autonomous delivery robots to expand their service areas beyond university campuses.

An investigation of the impacts of SADRs to pedestrians and bicyclists, which would likely increase in frequency with expansions to autonomous delivery systems reliant on the shared-use of transportation facilities, represents a second study contribution. Descriptive results from an administration of the PAR-D survey instrument to a university population with first-hand experience in the SADR deployment found that pedestrians tended to be more comfortable in sharing pathways with SADRs than bicyclists. However, model results revealed that individuals who stated being uncomfortable in sharing pathways with SADRs as a pedestrian or reported having to alter their intended path in the past due to an autonomous delivery robot operating on a sidewalk were less comfortable having to take evasive actions to avoid the trajectory of an oncoming SADR. Linking comfort in sharing transportation facilities to adoption experience, survey respondents who more frequently used autonomous food delivery services in the past tended to be more comfortable in taking evasive actions to avoid potentially more-severe interactions with SADRs as either a pedestrian or bicyclist. Yet, in more-severe SADR-bicyclist interactions, mode-specific experience should be considered given that survey respondents who bicycle around campus were less comfortable having to swerve to avoid a potential SADR-involved collision than respondents who drive around NAU's campus.

Given this study's findings and contributions, transportation policies and interventions addressing the likely introduction of SADRs to new settings and their expansion in current university settings should receive greater consideration. Foremost, goals to further motivate active transportation by improving the safe adoption of utilitarian walking and bicycling travel and increase sustainable travel mode shares may be further hindered if proactive measures are not taken to remedy those close SADR-involved interactions that will undoubtedly occur on many sidewalks in urban settings. If the current deployment of SADRs onto facilities shared by pedestrians, bicyclists, and emergent micromobility options (e.g., e-scooters) remains, as was found preferable by this study sample, then the management of sidewalks and programming of SADR routes must ensure these new freight technologies do not impede safe and efficient active travel. The rollout of demonstration projects rather than any untested full-scale deployment of SADRs should be pursued to help identify safety concerns expressed by new market segments and pathways where SADR operation is less of an impediment to pedestrians and bicyclists, as this study found that pedestrians or bicyclists who had previously altered their intended trajectory because of an approaching SADR were less comfortable having to navigate SADR encounters in which an evasive action would be needed to avoid a potential collision.

While this study contributes to behavioral and safety research on autonomous delivery robots, it is not without limitations. First, this study's administration of the PAR-D survey instrument as an intercept survey of a university population produced a convenient sample that does not represent a more general population. Although the adoption of this sampling area ensured that most participants were familiar with SADRs, the sociodemographic and economic characteristics of the study sample are unlikely to reflect the composition of a dense, mixed-use setting that may likely be a target for future SADR fleet deployments. Relatedly, the videos in the survey instrument's choice experiment were recorded in a controlled campus setting that is not likely to capture the complexity and nuance of interacting with an SADR as a pedestrian or bicyclist navigating an urban environment. Of note, although this study's sampling strategy was devised to increase the number and completeness of survey responses to be analyzed, only 15% of the final study sample included respondents with experience traveling around NAU's campus on a bicycle. Accordingly, future research should employ targeted sampling strategies toward bicyclists to better understand how this segment of active travelers may respond to a deployment of autonomous delivery robots on shared-use facilities. Finally, the responses recorded for this study are self-reported and thus may contain some measurement error introduced to its analysis. Although the administration of this study's original survey instrument generated new knowledge as to how SADRs operating in a real-world setting may impact the safety conditions for pedestrians and bicyclists, the collection of observed SADR-involved conflicts could provide more objective and complementary evidence needed to inform new policies and interventions.

Conclusion

The two studies described in this research report present early evidence on the observed and reported traffic safety conditions experienced by individuals interacting with SADRs on shared-use pathways. For the first study, field-recordings of SADRs operating in shared-use settings with pedestrians, bicyclists, and other human pathway users were collected and examined by adapting the surrogate safety measure of PET to identify the prevalence, location, and severity of SADR-involved interactions. Potential conflict- and site-level characteristics associated with the recorded severity of observed SADR-involved incidents were then defined by estimating an ordered logit model. Findings from this first study, which introduced the concept of a nested and dynamic conflict area to measure the PET for interactions involving vehicles with narrower dimensions than their travel lane, highlighted the challenges of safely introducing SADRs onto pathways and curb spaces shared by pedestrians and bicyclists who were noted as often having to alter their intended path to avoid a collision with these new low-speed automated delivery services. For the second study, a survey instrument with stated choice experiments aimed at detecting an individual's self-reported comfort in sharing pathways with SADRs as a pedestrian or bicyclist was administered to a college population with experience in the real-world commercial deployment of SADRs. Findings from this second study, which identified various personal attributes associated with SADR adoption levels and linked these and other individual characteristics to a survey respondent's perceived level of comfort for sharing pathways with SADRs as an active traveler, offered new insights on the future intention to adopt automated food delivery services and comfort in traveling alongside SADRs from a population with first-hand knowledge on the small-scale deployment of this new last-mile food delivery service.

Taken together, the research contributions from these two studies are intended to help inform future research on the adoption and operation of autonomous delivery robots and provide practitioners and policymakers an indication of how an emerging technology with a potential to improve freight mobility in urban settings may be adversely impacting the traffic safety conditions for sustainable travel modes. For researchers, this project's first study put forth a methodology for adapting an established surrogate safety measure to characterize conflicts on shared-use facilities that can be reapplied to understand the traffic safety conditions attributed to new freight delivery or mobility options that are being deployed on facilities originally designed for other pathway users. Moreover, model results from the project's second study that suggested revealed travel behaviors were associated with an individual's stated comfort level in sharing a transportation facility with an automated delivery robot should be further investigated to recognize the psychological barriers these devices may have on motivating active travel mode adoption. For practitioners and policymakers, a recognition of conflicts between SADRs and human pathway users and reported pedestrian and bicyclist discomfort in sharing pathways with SADRs that was found in this research project's first and second studies, respectively, have established a need for new transportation facility management strategies, refined routing programs, and potential revisions to the physical design of low-speed automated delivery services that ensure their safe introduction and continued operation on facilities originally designed for pedestrians, bicyclist, or other vulnerable roadway users.

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Data Management Plan

Products of Research

Primary data described and analyzed in this report were collected for its first and second studies. For the first study, which examined field-recorded videos of pedestrians and bicyclists interacting with sidewalk autonomous delivery robots (SADRs) on the main campus of Northern Arizona University (NAU), a data set of observed SADR-involved interactions was collected. This raw data set and subsequent versions of cleaned tabular data were analyzed to produce those tables and figures in this report's second chapter. For the second study, which analyzed the results from an administered original survey instrument to an NAU population, survey respondent data were collected. This second raw primary data set was cleaned, summarized, and analyzed by estimating statistical model, with results and other tabular data presented in the report's third chapter.

Data Format and Content

The tabular data sets collected and analyzed for this research report are formatted as comma separated values (.csv) files, with statistical analyses conducted using the open-source R programming language for statistical computing and graphics. These .csv data files and .R scripts have been uploaded to a Harvard Dataverse ("Replication Data for PSR-21-16") the contains the following content for the two studies:

- Study 1: Observed Sidewalk Autonomous Delivery Robot Interactions with Pedestrians and Bicyclists on Shared-Use Pathways
    - "starship_video_01_data-clean.R" is a script that merges the raw conflict ("conflict-review_master_v2.tab"), exposure ("exposure-review_master_v2.tab"), and bounding box ("bounding-boxes-cdp.tab") data sets to produce a cleaned study sample data set ("dat_pet_clean.tab").
    - "starship_video_02_models.R" is a script that produces the statistical modeling data set ("dat_pet_model.tab") used to perform the study's modeling analysis from the cleaned study sample data set ("dat_pet_clean.tab").
- Study 2: Reported Pedestrian and Bicyclist Comfort in Sharing Pathways with Sidewalk Autonomous Robots
    - "starship_survey_01_data-clean.R" is a script that imports and cleans the raw data set ("dat_pard_raw.tab") to produce the study sample data set ("dat_pard_clean.tab").
    - "starship_survey_03_models_v2.R" is a script that produces the statistical modeling data set ("dat_pard_model_v2.tab") used to perform the study's modeling analysis from the cleaned study sample data set ("dat_pard_clean.tab").

Data Access and Sharing

The data sets and analytic scripts used in this research report can be found in "Replication Data for PSR-21-16" on Harvard Dataverse (https://doi.org/10.7910/DVN/KWMCDM). Video files (.mov) associated with the first study will be retained on a password-protected external drive accessible by the Principal Investigator, which can be shared with the general public for research purposes upon request.

Reuse and Redistribution

Tabular data and associated scripts that are published on Dataverse or locally-stored video data may be reused and redistributed for research purposes with permission from this report's Principal Investigator.

Appendix: Perceptions of Autonomous Robots for Deliveries (PAR-D) survey instrument

Section I: Survey Participant Information

Please answer the following set of questions regarding your sociodemographic and economic background and general travel behaviors to the best of your abilities and as accurately as possible.

1. Which of the following best describes your current living accommodations in relation to NAU?
    - On-campus housing
    - Off-campus housing

2. What ZIP code do you currently live in?
    Note: Display only if "Off-campus housing" is selected for Question 1.

3. What is your age?
    - 18-24 years
    - 25-34 years
    - 35-44 years
    - 45-64 years
    - 65+ years

4. What is your gender?
    - Female
    - Male
    - Self-describe (please specify)
    - Prefer not to answer

5. Which racial/ethnic background do you identify with? Check all that apply.
    - White/Caucasian
    - Latino/Hispanic
    - Black/African American
    - Asian
    - American Indian or Alaska Native
    - Native Hawaiian or other Pacific Islander
    - Self-describe (please specify)
    - Prefer not to answer

6. What was your personal income during the past 12 months?
    - Below $15,000
    - $15,000 - $34,999
    - $35,000 - $49,999
    - $50,000 - $74,999
    - $75,000 - $99,999
    - $100,000 or above
    - Prefer not to answer

7. What is your current employment status? Check all that apply.
    - Full-time work (35 or more hours per week)
    - Part-time work (1-34 hours per week)
    - Full-time student
    - Part-time student
    - Retired
    - Unemployed and looking for work
    - Unemployed and NOT looking for work
    - Other (please specify)

8. Which best describes your educational status?
    Note: Display only if "Full-time student" or "Part-time student" is selected for Question 9.
    - Freshman
    - Sophomore
    - Junior
    - Senior
    - Master's student
    - Doctoral student

9. Which best describes your educational status?
    Note: Display only if "Full-time student" or "Part-time student" is not selected for Question 9.
    - High school degree or equivalent
    - Associate degree or some college
    - Bachelor's degree
    - Graduate degree (Masters, PhD)

10. Which ONE of the following ways do you mostly travel TO NAU?
    Note: Display only if "Off-campus housing" is selected for Question 1.

- Car
- Bus
- Bicycle
- Walk
- Other (please specify)

11. What are all the ways you travel AROUND NAU?
    - Car
    - Bus
    - Bicycle
    - Walk
    - Other (please specify)

Section II: Autonomous Delivery Vehicles

Please answer the following set of questions regarding your experiences with and present perceptions of sidewalk automated delivery robots to the best of your abilities and as accurately as possible.

12. How often do you use Starship robot delivery services to order food or drinks?
    - Never
    - Very rarely (one time per year or less)
    - Rarely (one time per month or less)
    - Occasionally (two or three times per month)
    - Frequently (one time per week)
    - Very frequently (two or more times per week)
    - Always (one or more times per day)

13. As a PEDESTRIAN or a BICYCLIST, have you altered your intended path because of an interaction with an autonomous Starship robot delivery service?
    - Yes
    - No
    - Don’t know

14. As a PEDESTRIAN, what is your comfort in sharing pathways with autonomous robot delivery services?
    - Very uncomfortable
    - Uncomfortable
    - Neutral

- Comfortable
- Very Comfortable
- Don't know

15. As a BICYCLIST, what is your comfort in sharing pathways with autonomous robot delivery services?
    - Very uncomfortable
    - Uncomfortable
    - Neutral
    - Comfortable
    - Very Comfortable
    - Don't know or don't ride a bicycle

16. For the following questions, imagine that in five years the use of autonomous robot delivery services is more common in public places. Please answer the following questions based on your opinion and judgment, with a score of 1 indicating least agreement and a score of 5 indicating most agreement.

    a. I intend to use autonomous delivery vehicles as a food or grocery delivery option.
    - 1 (Least agreement)
    - 2
    - 3
    - 4
    - 5 (Most agreement)

    b. Autonomous delivery vehicles will work well if sharing pathways with only pedestrians and bicyclists.
    - 1 (Least agreement)
    - 2
    - 3
    - 4
    - 5 (Most agreement)

    c. Autonomous delivery vehicles will work well if sharing roadways with only motorists.
    - 1 (Least agreement)
    - 2
    - 3
    - 4
    - 5 (Most agreement)

Section III. Choice Experiment

Please review the following videos imagining that you are the pedestrian or bicyclist who is encountering the autonomous delivery vehicle. Please answer the following set of questions to the best of your abilities and as accurately as possible.

17. [*Video: Pedestrian and Starship robot with post encroachment time (PET) = 1-3 seconds*]
    As a PEDESTRIAN, what is your comfort in sharing this pathway with the autonomous delivery vehicle?
    - Very uncomfortable
    - Uncomfortable
    - Neutral
    - Comfortable
    - Very Comfortable

18. [*Video: Pedestrian and Starship robot with PET = 0-1 seconds*]
    As a PEDESTRIAN, what is your comfort in sharing this pathway with the autonomous delivery vehicle?
    - Very uncomfortable
    - Uncomfortable
    - Neutral
    - Comfortable
    - Very Comfortable

19. [*Video: Bicyclist and Starship robot with PET = 1-3 seconds*]
    As a BICYCLIST, what is your comfort in sharing this pathway with the autonomous delivery vehicle?
    - Very uncomfortable
    - Uncomfortable
    - Neutral
    - Comfortable
    - Very Comfortable

20. [*Video: Bicyclist and Starship robot with PET = 0-1 seconds*]
    As a BICYCLIST, what is your comfort in sharing this pathway with the autonomous delivery vehicle?
    - Very uncomfortable
    - Uncomfortable
    - Neutral
    - Comfortable
    - Very Comfortable