EXPLORING CYCLIST-PEDESTRIAN INTERACTIONS IN SHARED SPACE USING AUTOMATED VIDEO CONFLICT ANALYSIS

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ABSTRACT

In the past decade, transportation planners worldwide have been incorporating shared space design elements as a way of creating pedestrian-friendly places. Streets incorporating shared-space principles tend to have reduced vehicle speeds and increased safety for vulnerable road users. In North American cities, a shared-space approach is rarely applied to non-motorized environments such as pedestrian malls, campuses, and parks. As cyclist and pedestrian speed distributions overlap, there is an opportunity to provide safe and convenient infrastructure to both through non-motorized shared spaces. Yet, little empirical evidence exists concerning the risk of pedestrians and cyclists interactions in shared spaces. To evaluate the safety of these spaces, a methodology is developed for semi-automated pedestrian-cyclist conflict analysis at high-volume intersections in non-motorized shared space. Measures of pedestrian and cyclist speed, angle of approach, pedestrian density and time-to-collision are analyzed to estimate the risk of pedestrian-cyclist interactions for different conditions. The methodology is then applied to a case study on the McGill University campus in Montreal, Canada, where pedestrians and cyclists co-exist with limited presence of motorized vehicles. Pedestrian and cyclist user trajectories were automatically extracted using a computer vision software to yield 2739 pedestrian-cyclist interactions for analysis. Speed and pedestrian density are shown to be negatively correlated, while conflict rate and density are positively correlated. Although a high pedestrian density increases the likelihood of conflict, it also reduces cyclist speed. Statistical differences were shown between conflict types defined based on intersecting angle and road user configuration.
INTRODUCTION

Two core objectives of traditional urban street design are efficient vehicle flow and adequate safety for all road users (1; 2). Physically separating road user types into dedicated areas was a relatively simple way to meet those objectives. In extreme examples, guardrails, pedestrian bridges, and tunnels were constructed to eliminate or reduce conflicts between road users while allowing for high vehicle speeds and flow. However, with new objectives including walkability and the quality and comfort of the pedestrian realm becoming integrated into policy, transport planners are increasingly conceiving streets as part of larger public and social life of residents, not solely as space for unimpeded automobile flow. In turn, there has been a trend away from traffic segregation, toward street design aimed at reducing vehicle speeds and increasing safety for vulnerable road users. In this framework, design principles based on creating pedestrian-friendly spaces, (for example, complete streets, traffic calming, or shared space), have gained prominence (3). In many North American cities, efforts to calm traffic on key commercial streets have been made, and several cities have implemented shared space design principles to achieve those goals (4; 5).

The pedestrian mall was designed as a pedestrian-only street (maximum user segregation) intended to improve pedestrian safety and enhance the pedestrian experience. Beginning in the 1960s and 1970s, hundreds of pedestrian malls were created in North America. Many were underutilized and did not achieve original objectives, and were converted back to conventional streets by the 1990s (6). One factor that plagued pedestrian malls was that pedestrian traffic alone was insufficient to support high levels of activity (6). Studies of six pedestrian malls found that shared malls (which allow for a limited amount of vehicular traffic) and transit malls (which incorporate transit lines), had significantly greater activity throughout the day resulting in lower commercial vacancy rates (6). Very few pedestrian malls in North America could be considered non-motorized shared spaces. The majority of pedestrian malls have a dismount policy for cyclists and forbid the use of rollerblades and skateboards. Despite the limited number of on-street examples of non-motorized shared spaces, several examples can be found where cyclists and pedestrians co-exist, including shared off-street paths, university and health service campuses, public parks, and sidewalks. In some cases, these environments are formally shared spaces for pedestrians and cyclists, while in others, unauthorized cyclists occupy the same space as pedestrians as the status quo.

Over the past decade, cycling demand in urban centers has increased dramatically and has not been met with a sufficient provision of infrastructure in many jurisdictions. As cyclists and pedestrians travel at relatively similar speeds compared to motorized vehicles, opportunities exist to provide safe and convenient infrastructure to vulnerable road users through non-motorized shared spaces in urban environments. Although pedestrians and cyclists currently co-exist along trails, parks, and campuses, few studies have sufficiently explored the level of safety provided by these facilities (7). It is worthwhile to investigate how pedestrians, cyclists, or other active users interact in non-motorized shared spaces with the objective of estimating safety, considering potential associated factors including user demand, speed, and approach, and weather conditions or other site-specific characteristics.

Studying the safety of vulnerable road users using traditional crash-based methods is almost impossible, as collisions between them are relatively rare and difficult to observe, requiring years of data collection for a robust analysis (8; 9). The purpose of this paper is to explore interactions between pedestrians and cyclists in shared space using semi-automated video conflict analysis. The study objectives are to; develop a method for automated video analysis of pedestrian-cyclist interactions at intersections in non-motorized shared space; to propose novel means of evaluating safe behavior in such environments, and; to present a case study on the McGill University Campus in Montreal, Canada where high volumes of pedestrians and cyclist interact. The following sections present the literature related to safety of shared spaces and traffic conflict techniques, the proposed methodology for automated conflict analysis, a description of the data, and results of the safety analysis at McGill University.
LITERATURE REVIEW

No consensus definition of shared space exists, though several have been proposed. Hamilton-Baillie (2) describes shared space as a space in which all road users interact “on the basis of informal social protocols and negotiation”. Under this definition, shared spaces are void of traffic control, including signs, signals, and markings of any kind. Physical separation, such as curbs, is either greatly reduced or removed. In place of formal traffic control, users “negotiate their way across the space employing an intricate and unspoken set of protocols” (2). Rather than defining shared space by street conditions, Kaparias (10) describes it as a set of streetscape treatments that create a more friendly environment for the most vulnerable users. Pedestrian friendly treatments include spaces with little or no delineation between pedestrians and vehicles and complete streets with physical separation that allocate an appropriate amount of space for all users. Karndacharuk, Wilson and Dunn (11) distinguish between shared streets and traffic calmed streets, exploring different sets of street design features with varying degrees of shared space elements across space and time. Herein, shared spaces are defined as streets that achieve user integration through limited signage and signals and little or no demarcation to separate pedestrians, cyclists, or vehicles. In North America, streets with shared space elements are most common in suburban areas with discontinuous street patterns and relatively low pedestrian and cyclist demand (12; 13). In contrast, Europe has numerous examples of high-volume, urban commercial streets with shared space design elements (2) in which relatively high volumes of pedestrians, cyclists, and vehicles can be accommodated at low speeds (2; 14; 15).

Several studies have measured safety of non-motorized shared spaces using manual techniques. Botma (16) evaluated the level of service of pedestrian-bicycle paths based on the frequency of interactions between users. Virklar (17) examined mixed-use trails in Missouri and Australia by manually observing speed, speed variance, demand, desired overtakings and potential conflicts. Karndacharuk, Wilson, and Dunn (14) proposed pedestrian performance measures based on demand, trajectories, dwell time, and stationary activities, finding that treatments with shared space elements aided in prioritizing pedestrian movement. Pedestrian density and vehicle speed were found to be inversely related. Kiyota (18) analyzed pedestrian and cyclist interactions on mixed-use sidewalks in Japan using speeds and separation distances extracted from video footage, finding that cyclist speed decreased as pedestrian density increased. In a survey, pedestrian density and cyclist speed were not found to significantly influence perceived risk (18).

Traffic conflicts are events that are sufficiently close to real crashes (19) and were first studied in the 1960s using human observation. Although initially for vehicular traffic, observation-based conflict techniques have been applied to non-motorized users and shared spaces. Kaparias et al. (20) developed a pedestrian-vehicle conflict analysis method (PVCA) based on an existing vehicle-vehicle technique. The technique uses four factors (time-to-collision, severity of evasive action, complexity of evasive action, and distance to collision point) to grade conflict severity. In a follow-up study, the PVCA method was applied in a before-after study to a site treated with shared space design elements (10). In a third study (15), the authors attempted to classify behaviour of pedestrians and drivers by observing reactions (path deviation and speed changes) as a function of vehicle approach speed and traffic density. Salamati et al. (21) developed a methodology for conflict-based assessment of pedestrian safety (CAPS). The CAPS adopts the PVCA method with an additional factor describing the road conditions.

Limitations of assessing conflicts using human observation include limited data volumes and potential subjectivity (22). Video-based sensors and computer vision techniques have improved objectivity and increased the amount of data that can be processed. Methods for automated conflict analysis have been designed and implemented for vehicular traffic by Ismail (23) and Saumier (24; 25), and have been applied to vulnerable users operating on traditional streets by Zangenehpour (26; 27). Yet, there have been essentially no studies which have applied automated conflict analysis to shared spaces or to conflicts between vulnerable users in either traditional or shared space environments. Schönauer et al. (28) studied the behavior of pedestrians, cyclists, and vehicles before and after the conversion of a high-volume roundabout in Austria to shared space. Though a 10% increase in safety was measured according to the selected indicators, only speed and separation distance were automatically extracted from collected...
video footage, and traffic conflicts were not explicitly captured. The lack of automated conflict analysis for studying either shared spaces or interactions between vulnerable road users represents a substantial gap in the existing literature. Given the thousands of examples of non-motorized shared spaces in North America alone, a study analyzing pedestrian and cyclist interactions in a non-motorized shared space could help inform policy, planning and design of those facilities.

**METHODOLOGY**

**Data Collection and Video Processing**

The collection of video traffic data and automated processing by computer-vision techniques has been presented in several past studies (24; 29-31). Video data is collected with an inexpensive video camera fixed to a telescoping fibreglass mast which, when mounted to existing infrastructure in the field, can be raised to a height of up to 6 metres. Traffic Intelligence (24; 29; 32) is an open-source object tracking software designed for extracting trajectories of road users from video footage, with a focus on safety analysis. Trajectories describing the position and speed of each road user at every frame of the video are automatically extracted from the footage. Road users are then classified as pedestrians, cyclists, or vehicles (27), determined by appearance, position, and speed. Considering the studied environment is a university campus with low occurrence of motorized vehicles, the classifier was constrained to identify pedestrians and cyclists only.

Shared space provides unique challenges for data processing which have been rarely discussed in the existing literature. First, slower overall speeds and smaller average size of road users requires adjustment to the tracking algorithm parameters. Second, the classification algorithm, as designed for traditional road environments, assumes that position in the roadway can assist in classification (pedestrians use sidewalks and crosswalks, while vehicles use the traffic lanes). In a shared space, position cannot be used because all users can use all parts of the facility. Speed is also not particularly powerful in determining class between pedestrians and cyclists. Speed distributions of cyclists and pedestrians overlap in traditional street environments, and even more so in shared space, where cyclist speeds are reduced because of interactions with pedestrians. These issues are expected to reduce the effectiveness of the classifier. Similar to Stipancic et al. (8), manual validation of the tracking and classification results was performed to reverse any classification errors and erroneous trajectories. Trajectories were filtered to isolate the desired interactions between one cyclist and one pedestrian.

**Computation of Surrogate Safety Measures**

Surrogate safety data has been successfully collected using video-based detection systems and extracted using computer vision techniques (29; 30). Traffic conflict techniques are popular for safety analysis using video data. Popular surrogate safety measures (SSMs) include time-to-collision (TTC) and post-encroachment time (PET). TTC is “the time required for two [users] to collide” (33) if their movements (speed and direction) remain unchanged. As the assumption of constant motion is often unrealistic, motion prediction methods are required. PET is the difference in time between two road users occupying the same location in space, or the conflict point (34). Accurate PET measurements are computed for any intersecting trajectories. Both measures are appropriate for the analysis of bicycle conflicts (8), though PET is preferred for this study because it captures a greater number of interactions and does not require motion prediction.

Once trajectories are extracted, PET is calculated for each interaction using a Python script to measure the time between consecutive road users occupying the conflict point. Determining PET threshold values has been discussed in studies including Zangenehpour et al (26). For vehicles, thresholds are typically 3-5 seconds for conflicts and approximately 1.5 seconds for dangerous conflicts. Because of reduced speeds and closer interactions in non-motorized shared space, a threshold of 5 seconds certainly does not represent a near crash event. For this study, a threshold for 5 seconds was used to describe users interacting, and a threshold of 2 seconds was used define road users conflicting.
Data Analysis

Cyclist Compliance Rate

Cycling is prohibited at the studied site at McGill University. As this is largely ignored by cyclists, the status quo is shared space between pedestrians and cyclists. A first step in determining safety is quantifying the cyclist compliance rate. Videos were manually reviewed to determine the number of cyclists riding and dismounted and the compliance rate was calculated. All dismounted cyclists were treated as pedestrians in the subsequent safety analysis.

Density-Speed-Safety Relationship

Although relationships between density, speed, and safety have been studied extensively for vehicular traffic, shared spaces require additional consideration. In this case, the information of interest is cyclist speed, pedestrian density, and conflict occurrence. The hypothesis is that the relationship between these variables should mirror expectations for vehicular traffic: increased pedestrian density should increase conflict frequency, similar to how congestion can increase the occurrence of collisions. Pedestrian density should also decrease cyclist speed, as there are more interactions to navigate. The relationship between pedestrian density, conflict frequency, and cyclist speed is plotted and analyzed. Correlation strengths are reported and the significance and strength of the relationships is tested using linear regression. A second objective is to observe if the occurrence of a conflict has an impact on the behaviour of a cyclist. The speed distributions of conflicting cyclists and all cyclists were compared using a Kolmogorov-Smirnov (K-S) test to determine if there was any statistically significant differences in terms of behaviour. The K-S test is a used to test equality between two continuous probability distributions, and is nonparametric, requiring no assumption regarding the shape of the probability distributions. The K-S statistic, D, represents the maximum difference between the two distribution functions.

Classifying Conflict Types

Conceptually, a single PET value does not necessarily represent a single level of risk, particularly when considering vulnerable road users and the variety of interaction types that can occur in a shared environment (noting that users are not constrained to specific lanes or directions). The final step is to present a possible classification scheme for conflicts in shared space. First, interactions were classified according to the angle between intersection trajectories. Type 1 interactions, “crossing from behind” or “overtaking”, involved trajectories in the same direction plus or minus 30 degrees. Type 2 interactions, “crossing from ahead” or “head-on”, feature trajectories intersecting in opposite directions plus or minus 30 degrees. Type 3, “crossing from the side” or “angled”, included all other interactions. Interactions were further classified according to which road user type reached the conflict point first. Interactions labelled Type P involved the pedestrian reaching the conflict point first, while Type B was used to label interactions with the cyclist arriving first. This yielded six unique conflict types for analysis. Characteristics of these conflict types were then explored. The 85th percentile of cyclist speed, 85th percentile of pedestrian density, and the conflict ratio (the ratio of the number of interactions with PET less than 2 seconds over the number of interactions with PET less than 5 seconds) were determined and plotted for each of the six interaction types. The significance of the differences between these plots was confirmed using a series of pairwise K-S tests on the distributions of density, speed, and PET. Finally, the proportions of each conflict type in different speed and density regimes were plotted and analyzed.

DATA DESCRIPTION

Site Selection and Data Collection

McGill University, located in Montreal, Quebec, Canada, has a downtown campus with approximately 40,000 students. The lower campus is accessed by two main gates, several secondary exterior entrances, and tens of building entrances. In the fall of 2015, pedestrians and cyclists were counted at the east main gates using passive infrared counters and pneumatic tubes. Six hours of video data were used to manually
validate and adjust the counts. On average 2,200 cyclists trips and 18,500 pedestrian trips crossed the east gates during school days. In May 2010, McGill University declared the lower campus a pedestrian-only zone. Vehicular use was restricted to service and maintenance vehicles, approximately 100 parking spaces were removed, and a cyclist dismount policy was initiated (35), which is largely ignored by cyclists.

In 2013, the University mandated the creation of a Cycling Working Group. In 2014, the 17-member group suggested treatments with shared space elements as a potential long-term solution for the lower campus (35). McGill administration recommended additional safety analysis related to mounted cyclists on the lower campus. The authors conducted a campus-wide survey to evaluate real and perceived risk of collisions between mounted cyclists and pedestrians on the lower campus. In April 2014, an online survey was distributed to 9,227 students, faculty, and staff, of which 872 useable surveys were returned. Respondents were asked to identify locations where they had been involved in a collision with a cyclist, had a “near-miss” with a cyclist (as a pedestrian), or had a “near-miss” with a pedestrian (as a cyclist), with near misses being defined as having to “stop abruptly or move out of the way to avoid a cyclist”. The self-reported near-misses were used to generate a heatmap, shown in Figure 1a. This heatmap aided in identifying three locations of interest: the area surrounding the east main gates, the curve around the McConnell Engineering building, and the lower campus main intersection, shown in Figure 1b.

This intersection is located 170 meters from the south main gate, has four approaches at irregular angles, and covers approximately 150 square metres. Daily cyclist volume is estimated to be 1,000 and pedestrian volume is estimated to be 20,000. The number of service vehicles passing through the intersection is negligible. Although the survey identified the intersection as the most dangerous location for pedestrians, no actual collisions have been reported. The perceived safety threat to pedestrians at this location made it an ideal location for a surrogate safety analysis. The camera was installed for four days in September 2015, and 12.7 hours of video data was collected. In total, 15,885 pedestrians and 1349 cyclists were detected, engaging in 2739 interactions (PET ≤ 5 seconds) and 1055 conflicts (PET ≤ 2 seconds).

**FIGURE 1** Heatmap of dangerous campus locations (a) and intersection of study (b)
Data Exploration and Validation

The shared space environment provides challenges to both detection and classification of road users. Therefore, prior to analysis, the data was explored and manually validated. With regards to detection rate, the false detection rate was determined to be 9.2%. False detections include any trajectories not linked to a road user, and primarily involve the tracking of shadows. Missed detections for cyclists were not explicitly considered because algorithm parameters were adjusted to ensure a majority of cyclists were detected. The detection rate for pedestrians is described in Figure 2a. This automated pedestrian count was manually validated approximately every 4000 frames for a total of 303 validations. The automated pedestrian count is consistently underestimated, and undercounting worsens as pedestrian volume increases. This result is similar to other pedestrian counters, as it is challenging to distinguish groups of pedestrians from individual pedestrians. The nonlinear relationship between the automated and observed count is mitigated by grouping the automated pedestrian count into six categories throughout the analysis.

Pedestrian demand is highly variable throughout the day. Demand peaks, seen in Figure 2b, occur hourly on the half hour, corresponding to the beginning of each class.

![Automated count vs observed count for pedestrians (a) and ten-second moving average of automated pedestrian count, vs time of day for September 16 (b)](image)

**FIGURE 2** Automated count vs observed count for pedestrians (a) and ten-second moving average of automated pedestrian count, vs time of day for September 16 (b)

In terms of classification for pedestrians, both precision (ratio of true classifications to all classifications) and recall (ratio of true classifications to all detected pedestrians) were very high at 97.5%
and 93.8% respectively. For cyclists, recall was still within expectations for the classifier (71.1%) but precision was very low (49.3%). This poor result is due mainly to the large disparity between pedestrian and cyclist volumes. Although pedestrians were misclassified as cyclists at a low rate, each misclassified pedestrian represents a large portion of all identified cyclists. If the classifier is to be used automatically in shared space environment, future work will be required to improve classification between non-motorized user types. For this study, false detections and missed classifications were corrected manually to improve the results presented below.

RESULTS

Cyclist Compliance Rate

The cyclist compliance rates at the main intersection, seen in Table 1, are relatively consistent across all four days where video was captured. Overall, approximately one out of every five cyclists complied with the dismount cycling policy on campus. The policy is clearly marked at both main gates where the majority of cyclists enter the lower campus.

### TABLE 1 Cyclist Compliance Rates at the Main Intersection

<table>
<thead>
<tr>
<th>Date</th>
<th>16-Sep</th>
<th>18-Sep</th>
<th>22-Sep</th>
<th>23-Sep</th>
<th>Entire Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclists - on bike</td>
<td>368</td>
<td>229</td>
<td>475</td>
<td>277</td>
<td>1349</td>
</tr>
<tr>
<td>Cyclists - off bike</td>
<td>113</td>
<td>44</td>
<td>92</td>
<td>43</td>
<td>292</td>
</tr>
<tr>
<td>Cyclists - total</td>
<td>481</td>
<td>273</td>
<td>567</td>
<td>320</td>
<td>1641</td>
</tr>
<tr>
<td>Compliance Rate</td>
<td>23.5%</td>
<td>16.1%</td>
<td>16.2%</td>
<td>13.4%</td>
<td><strong>17.8%</strong></td>
</tr>
</tbody>
</table>

Density-Speed-Safety Relationship

Influence of Density on Cyclist Speed and Conflicts

For each of the 1349 cyclists captured, average speed and pedestrian count were extracted. Figure 3a shows the relationship between cyclist speed and pedestrian density. Although a range of cycling speeds are observed for each pedestrian count value, the 25, 50, 75 percentile and maximum speed are observed to decrease as pedestrian density increases (median speed is 14.5 km/h at lowest density and 7.4 at the highest). The correlation between cyclist speed and pedestrian density was determined to be -0.36. Linear regression (with density as the only independent variable) showed that density is a statistically significant predictor of speed, at 99% confidence (t = -14.29), and that cyclist speed drops by over 1 km/h for every two additional pedestrians in the intersection.

As expected, the conflict rate, expressed as either conflicts/hour or conflicts/hour/pedestrian, increases as pedestrian density increases. The correlation between conflict rate and pedestrian density squared is 0.97 and is shown to be statistically significant by regression (again, with density as the only explanatory variable) at 99% confidence (t = 14.29). However, the relationship between the conflict rate and pedestrian density is almost entirely a result of low-speed conflicts. Figure 3b illustrates the relationship between conflict rate and pedestrian density for different cyclist speeds. In this analysis, low-, moderate- and high-speeds are defined as less than 9km/h (the 50th percentile), between 9km/h and 16km/h (the 85th percentile), and greater than 16km/h respectively. For different cycling speeds, the rate of conflicts/hour and conflicts/hour/pedestrian diverge as pedestrian density increases. The rate of conflicts/hour involving a cyclist traveling at low-speed (blue column) increases as a higher order polynomial as pedestrian density increases, whereas the rate involving moderate- and high-speed cyclists remain relatively stable as pedestrian density increases. The rate of conflicts/hour/pedestrian involving a cyclist traveling at low-speed (blue line) also increases as a higher order polynomial as pedestrian density
increases. On the other hand, the rate involving moderate- and high-speed cyclists decreases steadily as pedestrian density increases. Note that pedestrian density used in this study is not a true density measure but rather the automated pedestrian count. The count and the pedestrian density are linearly related since the area under analysis remained constant throughout the study.

**FIGURE 3** Box plot of cyclist speeds for different pedestrian densities (a) and conflict rates vs. pedestrian density for different cycling speeds (b)
Influence of Conflicts on Cyclist Speed
The distributions of speed for conflicting and all cyclists is presented in Figure 4. Visually, the distribution for conflicting cyclists is shifted to the left. Furthermore, the mean speed of conflicting cyclists is approximately 1 km/h lower. A K-S test showed that the differences between the distributions were statistically significant at 99% confidence ($D = -0.1752$), and the mean speed for conflicting cyclists is lower. The fact that conflicting cyclists are travelling slower on average indicates that there may be a mediating effecting of conflicts on speed. That is to say that cyclists engaging in a conflict are somehow modifying their behavior and therefore improving safety.

FIGURE 4  Distribution of speeds for all cyclists and conflicting cyclists

Classifying Conflict Types
Characteristics of Conflict Types
PET alone may be insufficient to indicate the relative risk of a conflict. Particularly when considering vulnerable road users and the variety of interaction types that can occur in shared space, a single PET value does not necessarily represent a single level of risk. In this study, it is hypothesized that conflicts and interactions can be classified into different groups based on intersecting angle and road user configuration (see Methodology above), and that these groups are statistically different based on the three dimensions of cyclist speed, pedestrian density, and PET. Plots of each of the six conflict types described earlier, are provided in Figure 5. These simple visual representations, which illustrate the 85th percentile of speed, 85th percentile of density, and conflict ratio, were used to make initial observations which could be confirmed through statistical testing. The range of the axis is provided in parentheses (speed [12-17 km/h], density [7-13 pedestrians], and ratio of conflicts to interactions [0.2-0.6]). The plots are also an easy visualization of the relative unsafety of each conflict type, as the smaller the triangle, the safer a conflict type is likely to be. Based on the plots, three initial observations were made:
1. Density is constant between conflict types.
2. Speed is higher for each Type B conflict compared to its Type P counterpart (the speed of 1B is higher than 1P, and so on).
3. The ratio of conflicts/interactions is lower for Type 3 conflicts compared to Type 1 and Type 2 (when interacting at an angle, there is a lower probability that their PET will be less than 2 seconds).

These observations were tested using pairwise K-S tests, the results of which are summarized below:

1. There is no significant difference in density between any conflict types.
2. There is a statistically significant difference in the speed distributions for Type 1P and Type 1B conflicts (97% confidence, D = -0.145), with speeds in Type 1P being lower. Although the speeds are also lower for Type 2P and 3P, the differences are not statistically significant.
3. PET values are higher for Type 3B compared to 1B and 2B (at 99% confidence by k-s test) and higher for Type 3P compared to 1P and 2P (at 99% confidence by k-s test). Higher PET values relate to fewer dangerous conflicts.

Statistical differences were verified in two of the three considered dimensions, supporting the hypothesis that there are different conflict types, and that the type of conflict, in addition to the PET, could be used to indicate the level of risk or safety.

**Conflict Occurrence in Different Environments**

With the relative safety of each conflict type explored, the final step was to determine if the occurrence of each conflict type was influenced by either the pedestrian density or cyclist speed. Low, medium, and high densities and speeds were categorized by splitting the data at the 50th and 85th percentiles of speed and density. Radar plots were again created to show the proportion of each conflict type occurring during each of the six speed and density scenarios, shown in Figure 6. The orientation of these plots reflects the relative direction of road users: Type 2, head on, are at the top, Type 3, from behind, are at the bottom, and Type 3, from the side, are to the left and right. Type B conflicts are on the left, and Type P conflicts are on the right.

Considering density, the plotted polygon is observed to get thinner at high density (low and medium density are substantially similar). This demonstrates that at high densities, crossing from the side interactions are more likely to occur than other types of conflicts, and are more likely to occur at high densities than at medium or low densities. While this may be intuitive, as more pedestrians means more maneuvering, means less opportunity for head-on or passing interactions. Considering speed, the graph again gets slightly thinner, but also shifts towards Type B conflicts at high speeds. Crossing conflicts and bike first conflicts are more probable than other conflict types at higher speeds. As demonstrated in Figure 5, Type B conflicts tend to have higher speeds, and so these types are expected to be more likely when cyclists are travelling at high speeds. This result shows that, not only are there statistical differences between conflict types, but that the likelihood of experiencing a given conflict type changes with density and speed.

**CONCLUSIONS**

This paper proposes a methodology for a semi-automated pedestrian-cyclist conflict analysis at intersections in non-motorized shared spaces to investigate the relationships between cyclist speed, pedestrian density, conflict severity and conflict types. Four out of five cyclists do not comply with the dismount policy, and the site on McGill’s lower campus is therefore shared space as the status quo. However, this does not mean that cyclists ignoring the policy are creating high risk for pedestrians. Although the definition for conflicts was set in this study as a cyclist-pedestrian interaction with a PET < 2 seconds, future work should focus on defining the most appropriate PET thresholds for shared spaces.
FIGURE 5 Characteristics of conflict types (proportion of interactions <2 sec, 85th percentile of pedestrian density, and 85th percentile of cyclist speed in km/h)
FIGURE 6 Proportion of conflict types based on pedestrian density and cyclist speed
Speed and pedestrian density are shown to be negatively correlated, while conflict rate and density are positively correlated. Although a high pedestrian density increases the likelihood of conflict (and therefore, a collision), it also reduces cyclist speed. High cyclist speeds (which translates into a greater kinetic energy and therefore a greater severity of crash) are observed to occur only at low densities. Therefore, high crash risk and high crash severity are not present at the same time, making the occurrence of severe crashes highly unlikely. This outcome mirrors behaviour of vehicular traffic (congestion or traffic control), and supports the concept of safety in numbers. Furthermore, cyclists involved in conflicts tend to travel at a lower speed compared to all cyclists. This shows that there is some mitigating effect of conflicts on cyclist speed, or that cyclists change their behaviour when engaging in conflicts with pedestrians.

The overall conflict rate increases as pedestrian density increases, however this relationship is not consistent across all cyclist speeds. When considering the relationship between the conflict rate and the pedestrian density, the differences for low-, moderate, and high-speed cyclists are apparent. The rate of conflicts/hour increase as a second-order polynomial when involving a low-speed cyclist, whereas the rate is stable for moderate and high-speed cyclists as pedestrian density increases. The relationship between the rate of conflicts/hour/pedestrian and the pedestrian density has even greater variation across cyclist speeds: the rate increases as a second-order polynomial when involving a low-speed cyclist, whereas the rate decreases steadily for moderate and high-speed cyclists.

Statistical differences were shown between conflict types defined based on intersecting angle and road user configuration. First, conflicts in which the pedestrian reaches the conflict point first tend to have lower cyclist speeds (although the K-S test only showed a significant difference for Type 1 or approaching from behind conflicts). This result matches intuition, in that, when pedestrians cross in front of cyclists, the cyclist is able to slow down. However, if a cyclist crosses in front of a pedestrian, it is more likely that they will speed up to avoid a collision. Second, when road users cross at an angle (Type 3 interaction) it is significantly less likely that they will be involved in a dangerous conflict. When approaching at an angle, both road users are likely to have better awareness of each other, and more opportunity to avoid a conflict. The occurrence of specific conflict types was also observed to change based on pedestrian density and cyclist speed. Interestingly, increasing density also increases the likelihood of Type 3 interactions. Because this interaction type is less likely to create conflicts, high density environments are safer both because of a reduction in cyclist speed, and because it breeds safer conflict types. Future work should focus on conflict types and assessing their relative risk in different environments, particularly in shared space, as unrestricted movement breeds more and more unique interaction types. Furthermore, although these results point towards a safe environment and safe behaviour, further study is required, including a potential for a before and after study if the dismount policy is repealed.

Dismount policies for cyclists tend to occur on high-volume pedestrian facilities such as pedestrian malls and public parks. Policies that limit the movement of cyclists are seen as an acceptable trade-off to improve safety for pedestrians. The results in this study suggest that pedestrian facilities experiencing high-density pedestrian traffic may in fact be the safest environments to integrate pedestrians and cyclists. Further research into pedestrian and cyclist conflicts in different environments will allow for the development of a comprehensive set of guidelines that would inform policy and design of non-motorized shared spaces, including parks, campuses, trails and pedestrian crossings along protected bikeways.

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