**Microscopic Behavioural Analysis of Cyclists and Pedestrians Interactions in Shared Space**

<table>
<thead>
<tr>
<th>Journal:</th>
<th>Canadian Journal of Civil Engineering</th>
</tr>
</thead>
<tbody>
<tr>
<td>Manuscript ID</td>
<td>cjce-2018-0777.R2</td>
</tr>
<tr>
<td>Manuscript Type:</td>
<td>Article</td>
</tr>
<tr>
<td>Date Submitted by the Author:</td>
<td>03-May-2019</td>
</tr>
<tr>
<td>Complete List of Authors:</td>
<td>Alsaleh, Rushdi; University of British Columbia, Civil Engineering Hussein, Mohamed; Mcmaster University Department of Civil Engineering Sayed, Tarek; University of British Columbia, Civil Engineering</td>
</tr>
<tr>
<td>Keyword:</td>
<td>pedestrian-cyclist interactions, shared space, shared space modeling, microscopic behavioural analysis, cyclist behaviour</td>
</tr>
<tr>
<td>Is the invited manuscript for consideration in a Special Issue?:</td>
<td>Not applicable (regular submission)</td>
</tr>
</tbody>
</table>
Microscopic Behavioural Analysis of Cyclists and Pedestrians
Interactions in Shared Space

Rushdi Alsaleh, M.Sc. (Corresponding Author)
Ph.D. Student and Research Assistant
Department of Civil Engineering
University of British Columbia
6250 Applied Science Lane,
Vancouver BC, Canada V6T 1Z4
Email: rushdi.alsaleh@ubc.ca

Mohamed Hussein, Ph.D.,
Assistant Professor,
Department of Civil Engineering
McMaster University
1280 Main Street West
Hamilton, ON, Canada, L8S 4L7
Email: hussem9@mcmaster.ca

Tarek Sayed, Ph.D., P.Eng.
Professor
Department of Civil Engineering
University of British Columbia
6250 Applied Science Lane,
Vancouver BC, Canada V6T 1Z4
Email: tsayed@civil.ubc.ca

Submission Date: May. 8th, 2019
ABSTRACT

This study investigates the microscopic interaction behaviour between cyclists and pedestrians in shared space environments. Video data was collected at the Robson Square shared space in downtown Vancouver, British Columbia. Trajectories of cyclists and pedestrians involved in 208 interactions (416 Trajectories) were extracted using computer vision algorithms. The extracted trajectories were used to define different indicators for the analysis. The indicators included the speed and acceleration profiles and the longitudinal and lateral distances between road users during different phases of the interactions. The study also investigated the collision avoidance mechanisms employed by road users to avoid collisions with other shared space users. The collision avoidance mechanisms included changing the walking/cycling speed and changing the movement direction. The results showed that the collision avoidance mechanisms depend on the shared space density and the space available for road users. The study identified a set of parameters that can be used to calibrate a microscopic cyclist-pedestrian modeling platform to represent the behaviour of pedestrians and cyclists in shared space environments.

Keywords: shared space, pedestrian-cyclist interactions, shared space modeling, microscopic behavioural analysis, cyclist behaviour.
INTRODUCTION

Many cities and road authorities are adopting policies that aim at promoting active modes of transportation such as walking and cycling. Encouraging active transportation supports the cities’ sustainability goals and reduces traffic-induced air pollution and congestion. As well, active modes of transportation help road users to adopt a healthy lifestyle and increase their level of physical activity which have numerous health benefits. The "Open Streets" program (Ciclovia) represents one of the policies that are gaining popularity in many cities in North America to encourage active road users of all ages and abilities to share the road. The program involves the temporary closure of selected city streets to motorized traffic and creating non-motorized shared space areas for social and recreational activities. By 2016, around 122 cities in the United States have hosted an “Open Street” program, including New York City and Los Angeles that have more than 100 thousands participants per event (Hipp et al. 2017). Similar “Open Street” programs were hosted in other cities such as Vancouver, Calgary, and Vienna.

The “Open Streets” program was inspired by the emerging concept of “shared space”. The shared space concept is established based on the recent findings in behavioral and environmental psychology and the evolution of the risk compensation theory (Adams 1995; Hamilton-Baillie 2008). Shared spaces are areas where there is no obvious segregation between road users, so that the right of way is shared by all road users. The access of motorized vehicles to the shared space area can be prohibited to create non-motorized shared spaces, which provides a safe and comfortable environment for non-motorized road users. Despite the emerging popularity of the shared space concept, limited studies have investigated the interaction behavior of active road users in such facilities. In addition to the difficulty of analyzing the behaviour of active road users in general, studying the behaviour of non-motorized road users in shared space environments is more challenging. Unlike conventional roads, the shared space concept provides road users with
the freedom to move in the whole area of the facility without being restricted to use predefined
paths (e.g. sidewalk or bike lanes). Thus, the frequency of interactions between road users and the
behavior during interactions in shared spaces can differ significantly than the corresponding
behaviour in conventional streets.

Microscopic simulation modeling of road user dynamics has been advocated as a promising
tool to analyze road user behavior in different facilities. Adopting a valid simulation model to
analyze road user interactions in shared space areas can provide a powerful tool that helps planners
and engineers to assess the level of service and safety of road users of shared space facilities.
However, existing simulation packages are inadequate to model the microscopic behaviour of road
users in shared space facilities (Gibb 2015). Recently, several agent-based simulation models that
better reflect road user behaviour have been developed (Hussein and Sayed 2015; Hussein and
Sayed 2017; Liu et al. 2014). For example, a pedestrian simulation model was developed at the
University of British Columbia to study the behavior of pedestrians during interactions with other
pedestrians and objects in the walking environment (Hussein and Sayed 2015; Hussein and Sayed
2017). The model relies on the identification of the rules of interactions between pedestrians,
which are usually extracted from comprehensive analysis of pedestrian behaviour. The results
reported in a recent study that applied the model to analyse pedestrian interactions on the Brooklyn
Bridge pedestrian/bike path (Hussein and Sayed 2018) suggests that the model can be expanded
to address pedestrians-bikes interactions in non-motorized shared spaces. However, such a task
should be preceded by a comprehensive study to analyze road user behaviour in shared spaces.

Therefore, this study investigates the microscopic interaction behaviour between cyclists
and pedestrians in a non-motorized shared space. Video data were collected at the shared space of
Robson Square in downtown Vancouver. Computer vision algorithms were applied to detect and
track pedestrians and cyclists from video footage. The extracted trajectories were used to define
different indicators that are used to analyze interaction behaviour of road users, including speed
and acceleration profiles, longitudinal and lateral distances between road users during different
phases of the interaction. Furthermore, the study identifies several parameters that can be used to
model such interaction in the microsimulation model.

PREVIOUS WORK

Shared Space Concept

Shared space is an emerging concept of urban design that supports pedestrian and cyclist
movements with slower vehicles (typically, 30 km/hr) and was shown to have safety, economic,
and quality of life benefits (Swinburne 2005; Akkar 2005). These schemes of street design
encourage the integration of road users (pedestrian-friendly environment) by reducing the
segregation between road users and decreasing the dominance of motorized vehicles (Kaparias et
al. 2012). Several studies showed documented benefits of shared spaces. For example, converting
Kensington High Street, a busy route in London, to a shared space area was shown to have a
significant improvement in pedestrian safety (pedestrian collisions were reduced by about 64%)
and increase in pedestrian activity levels (Swinburne 2005). As well, the conversion of a five-leg
intersection in Oosterwolde, Netherlands to a paved open area for all users resulted in a reduction
in severe collisions despite the increase in traffic volume at the intersection (Hamilton-Baillie
2008).

The benefits of shared space schemes are also extended to improve the attractiveness of
the urban realm (Hamilton-Baillie 2008), and reduce the traffic-related air pollution (Shu et al.
2016). As well, economic and urban revitalization and investments growth were clearly observed
after a remodeling of the Grey’s Monument area, Newcastle into a public space area (Akkar 2005).
Despite the benefits of shared space areas, concerns were raised about the severity of interactions
between non-motorized road users. Collisions between the vulnerable road users (cyclist-
pedestrian collision) can lead to severe consequences, especially for pedestrians, who are more
likely to suffer from severe injuries that can lead to death if involved in collisions with cyclists
(Graw and Konig 2002).

**Road User Behaviour in Shared Spaces**

Only few studies have investigated the behaviour of road users in shared spaces. For
example, Hussein et al. (2016) studied the safety of pedestrians and cyclists in the shared space of
Park Avenue during the summer street program in New York City. The study utilized computer
vision techniques in extracting the trajectory of road users and investigating their speeds and gait
parameters during the summer street program. Schonauer et al. (2012) studied the behaviour of
road users before and after converting a complex roundabout in Austria into a shared space area.
The study concluded that the speed distributions of all modes became narrower in the shared space
area, which can be explained by the smoother movements and less stop and go conditions in shared
spaces compared to complex roundabouts. Kiyota et al. (2000) studied the behaviour and the safety
of pedestrians and cyclists in a non-motorized shared space in Japan and found that the perceived
risk by pedestrians becomes higher as the passing distance between the cyclists and pedestrians
decreases. Cyclist speed was shown to be affected by pedestrian density, and lower cyclist speeds
were observed at higher pedestrian densities (Essa et al. 2018). Beitel et al. (2018) studied the
behaviour and safety of pedestrians and cyclist on a non-motorized shared space area in McGill
University, Montreal. The study classified the conflicts between the cyclists and pedestrians based
on two criteria: the angle between their intersecting trajectories and who reaches first to the conflict
point. The results showed that speed of cyclists decreases as pedestrian density increases, and the
conflict rate between cyclists and pedestrians increases with pedestrian density. Furthermore,
previous studies used several parameters to describe the behaviour of pedestrians or cyclists in
shared spaces or segregated roads/paths. These parameters include speed and acceleration profiles (Twaddle and Grigoropoulos 2016; Ma and Luo 2016; Afghari et al. 2014), lateral distance and/or headway (Luo et al. 2015; Hussein and Sayed 2017; Hoogendoorn and Daamen, 2016), pedestrian gait parameters (Alsaleh et al. 2018; Hussein and Sayed 2015; Guo et al. 2016; Hediyeh et al. 2014).

The literature review shows that most studies did not investigate the microscopic interaction behaviour between cyclists and pedestrians in non-motorized shared spaces. Investigating such interaction behaviour is important for modeling these interactions in microsimulation models. Therefore, this study aims to 1) investigate the microscopic interaction behaviour between cyclists and pedestrians in shared space environments; 2) investigate the collision avoidance mechanisms and the factors affecting the selection of the collision avoidance mechanisms employed by road users to avoid collisions with other shared space users; and 3) identify several parameters that can be used to model cyclists and pedestrians interactions in microsimulation models.

METHODOLOGY

Video data was collected at the busy shared space of Robson Square in downtown Vancouver. Robson square is a non-motorized shared space area that is characterized by high pedestrian and cyclist activities. Pedestrians and cyclists were automatically tracked and their trajectories were extracted from the video footage using Computer Vision (CV) algorithms. The interacting road users were classified based on the interacting angle into three categories: [i] interactions with shared space users moving in the same direction, [ii] interactions with opposing shared space users, and [iii] interactions with crossing shared space users. The speed and acceleration profiles and relative spatial profiles were used to analyze the interaction behaviour of pedestrians and cyclists in different cases. The following sub-sections summarize the details of
each of the following tasks: data collection, road user tracking, extraction of spatial, speed and acceleration profiles, and interaction identification and analysis.

### Data Collection

Video data were collected at a busy non-motorized shared space, located in Robson Square in downtown Vancouver, as shown in Figure 1. The city of Vancouver considered the permanent closure of Robson Street, between Hornby Street in the west and Howe Street in the east, for motorized traffic in order to provide a comfortable and safe plaza for vulnerable road users in the heart of downtown. The area is a place for many recreational and business facilities, including the Vancouver Art Gallery, the Robson Square ice rink, the Vancouver Supreme Court, among others. The area is an active environment for walking and cycling especially in the summer season. Pedestrian-cyclist interactions are frequently observed in the shared space area. Eighteen hours of video data were collected in daylight over several days in August and September 2016. Video data were collected using a video camera installed near the western entrance of the shared space, as shown in Figure 1.

### Road user Tracking

The automated extraction of road user trajectories from video footage was conducted using a video analysis system that has been developed at the University of British Columbia (Saunier and Sayed 2006). The system employs computer-vision algorithms to detect, track, and classify road users in traffic scenes. The detection of the road users is carried out using an implementation of the Kanade–Lucas–Tomasi (KLT) feature-tracking algorithm (Lucas and Kanade 1981) (Tomasi and Kanade 1991). The algorithm detects distinct points (features) on moving objects in the video scene. The algorithm is capable of differentiating between features that belong to road users (e.g. pedestrians, cyclists) and that are part of the background.
Typically, multiple features are tracked on each road user each video frame. Clustering of features is important to determine which group of features belongs to the same road user. The clustering algorithm uses different cues to cluster the tracked features, including the spatial proximity of features and their dynamical similarities. The subsequent step in the analysis is the classification of road users. The classification process is then used to discriminate between trajectories that belong to different categories of road users (e.g. pedestrians and cyclists). The main cues in the classification of road users’ trajectories are the frequency harmonics extracted from their speed profiles (Zaki and Sayed 2013). Several previous studies validated the accuracy of the system and found to be satisfactory (Ismail et al. 2010; Zaki and Sayed 2013; Ismail et al. 2013).

However, an essential task prior to the aforementioned procedures is to create a mapping between video image plane coordinates and the real-world coordinate system, so that the spatial and temporal information of the tracked trajectories are known in the actual coordinate system of the location being analyzed. This task is known as the camera calibration, and is described in details in Ismail et al. (Ismail et al. 2013). The overall analysis procedures are illustrated in Figure 2.

One of the limitation of the using KLT algorithm for tracking cyclists and pedestrians is the over-grouping problem which occurs when road users (e.g. pedestrians) move closely together or when one feature is detected moving consistently with two other distinct groups (Saunier and Sayed 2006). Moreover, the KLT tracking algorithm may not handle occlusion very well as the trajectories may be disrupted by occlusions (Saunier and Sayed 2006). In this study, the tracking parameters were carefully selected and tuned to minimize tracking errors. As well, the tracking was checked manually for each road user involved in the interactions to ensure the accuracy of the tracking of each interaction. Other tracking techniques and a benchmark for the evaluation of
different multi-object tracking methods can be found in (Milan et al. 2016).

**Extraction of Spatial, Speed and Acceleration Profiles**

The road user trajectories record the spatial coordinates and the instantaneous speed at each video frame (1/30 second). The trajectory is defined along the trajectory lifetime (n video frame) as a finite set of tuples (Ismail et al. 2013), as shown in Equation 1:

\[
T = \{(X_1, Y_1, V_{X,1}, V_{Y,1}, \ldots, X_i, Y_i, V_{X,i}, V_{Y,i}, \ldots, X_n, Y_n, V_{X,n}, V_{Y,n})\}
\]  

(1)

Where \(i = \{1,\cdots,n\}\) is a discrete temporal index, \(X_i\) and \(Y_i\) are the spatial coordinates of the road user at the frame \((i)\), and \(V_{X,i}, V_{Y,i}\) are the corresponding velocities. A speed profile \((S)\) for each road user is defined along the trajectory lifetime as \(S = \text{norm}(V_x, V_y)\), with \(V_x\) and \(V_y\) are the velocity vectors of length \(n\), for the \(X\) and \(Y\) coordinates, respectively.

Estimation of pedestrian and cyclist acceleration profiles from the noisy walking speed signal obtained from the video data required first smoothing of the speed time series. The road user acceleration profiles can be derived from their smoothed speed profile as follows:

\[
a = \frac{\Delta(S)}{\Delta t} = \frac{S_i - S_{i-\delta}}{\delta}
\]

(2)

Where \(a\) is the acceleration profile and it is defined by a time series of length \((n - \delta)\), \(i = \{\delta + 1, \cdots, n\}\) is a discrete temporal index, and \(S_i\) is the smoothen speed at the \(i^{th}\) video frame. The analysis procedures of road user trajectory are illustrated in Figure 2.

A validation of the accuracy of the road user trajectory extraction process was carried out by comparing a sample of 100 trajectories with the manually measured speeds of the road users based on the time required to traverse a known distance in the video scene. The mean percentage absolute error was 6.6 % (absolute error of 0.11 m/s for pedestrians and 0.18 m/s for cyclists), which is considered low and to not affect the findings. In this study, similar to many previous
studies of shared spaces as (Beitel et al. 2018), road user classification was carried out manually to avoid any misclassification of road users in the shared space area.

### Interaction Identification and Analysis

Video data were manually reviewed in order to define different types of interactions between pedestrians and cyclists in the shared space. Observed interactions were classified into three main categories based on the interacting angle (Beitel et al. 2018):

- Interactions with slower shared-space users moving in the same direction: These interactions involve cyclists and pedestrians moving in the same directions (difference in movement direction = $0^\circ \pm 30^\circ$).

- Interactions with opposing shared-space users: These interactions involve cyclists and pedestrians moving in the opposite directions (difference in movement direction = $180^\circ \pm 30^\circ$).

- Interactions with crossing shared-space users: These interactions include all other cyclist-pedestrian interactions.

A total number of 208 interactions were observed during the 18 hours of the analyzed video data. The trajectories, speed profiles, acceleration profiles of all pedestrians and cyclists involved in at least one of the previous interactions were considered for the analysis. In the analyzed interactions, an evasive action was taken by at least one of the road users involved in an interaction to resolve the conflict. Generally, two types of evasive actions were observed: 1) changing cycling/walking speed, and 2) swerving maneuvers.

For each shared-space user involved in the interaction, the start and end of each interaction were identified manually from both the speed profile and the trajectory of the road user. The road user trajectories were used to compute the relative longitudinal and lateral distance between the
interacting road users at different phases of the interaction. Test of significance (two-sample $t$-test) is used to investigate the significance of change in road user behaviour during the interaction.

**DISCUSSION OF RESULTS**

**Interactions with Shared-Space Users Moving in the Same Direction**

This type of interactions occurs when a faster shared-space user is hindered by another slower user, moving in the same direction (difference in movement direction = $0^\circ \pm 30^\circ$). It is frequently observed in shared-space areas due to the significant difference in the operational speed between different categories of shared-space users (Department of Transport and Main Roads of Queensland State 2014). Faster shared-space users (typically, cyclists) tend to apply at least one of the following two collision avoidance mechanisms to avoid collision with the slower shared-space user (pedestrians, in most cases): [i] reduce their speeds to keep adequate space with the slower shared-space users (following -maneuver), or [ii] apply swerving maneuvers to overtake the slower shared-space users (overtaking maneuvers). In most cases, the overtaking maneuvers are associated with a change in speed of the faster shared-space user. The factors affecting the selection of the collision avoidance mechanism and a detailed description of the two strategies are discussed in more details in the following subsections.

1) **Selection of the Collision Avoidance Strategy**

As discussed earlier, road users involved in interactions with other road users moving in the same direction may choose to follow slower road users or overtake them. Reviewing the interactions suggested that the selection of the collision avoidance mechanism taken by the faster road users mainly depends on two factors; [i] the available lateral space for the faster shared-space user, and [ii] the shared space density during the interaction. When the density of the shared space increases, it becomes more difficult for faster road users to swerve and overtake slower pedestrians.
Similarly, when the available lateral space for the faster road users is limited, due to barriers or other street furniture, faster road users may be forced to reduce their speed and follow slower road users.

A binary logit model was developed to assess the probability of selecting each of the two collision avoidance strategies. One hundred and five cyclist-pedestrian same-direction interactions were reviewed manually, and the collision avoidance strategy adopted by the faster road users were recorded. The model is expressed as follow:

\[
P_{\text{overtaking}} = \frac{1}{1 + e^{-(a_0 + a_1 \cdot \text{Dist} + a_2 \cdot \text{Den})}}
\]  

Where \( P_{\text{overtaking}} \) is the probability of performing an overtaking maneuver, \( \text{Dist} \) is the maximum available lateral distance for the faster road during the interaction (in meters), \( \text{Den} \) is the average shared space density (in road user / m\(^2\)), and \( a_0, a_1, \) and \( a_2 \) are model parameters. The density is calculated over the area of 12.5 m\(^2\) that covers the interacting road users. This area is selected to reflect the modelled area and the presence of sitting tables for pedestrians and is consistent with other studies (Hussein and Sayed 2018; Liu et al. 2014).

The estimated model parameters are presented in Table 1. The coefficients of the two explanatory variables were significant at 95%. The estimated parameters confirm that probability of the faster cyclist to execute overtaking maneuvers increases as the density of the shared space decreases and the available space increases as shown in Figure 3. The average value of the shared space density and available space for the two collision-avoidance strategies are presented in Table 2.

a) Description of the Following Strategy

Sixty-five pedestrian-cyclist interactions that involved following maneuvers were analyzed in this study. The speeds of all shared-space users involved in the maneuvers were extracted, as
well as the longitudinal distances between each pair of shared-space users in conflict. Figure 4 shows an example of a following maneuver that involves a faster cyclist and slower pedestrian. The cyclist’s and pedestrian’s speed profiles, acceleration profiles, and the longitudinal distance profile between the cyclists and the pedestrian are shown in Figure 5. As shown in the figure, the interaction can be classified into three phases:

1. Phase 1: the cyclist is travelling at a normal cycling speed (4.33 m/s in this example) as he/she is approaching a slower walking pedestrian.

2. Phase 2: at a specific distance from the slower pedestrian (4.68 meters in the current example), the cyclist started to reduce the speed to avoid collision with the slower pedestrian. The average longitudinal distance at which cyclists started to reduce speed for the 65 interactions analyzed was found to be 4.46 m, with a standard deviation of 1.29 m. The average deceleration value for the 65 interactions was found to be 0.81 m/s\(^2\), with a standard deviation of 0.40 m/s\(^2\). This phase can be considered as an evasive action taken by the cyclist to avoid collision with the slower pedestrians during the high-density periods in the shared space.

3. Phase 3: the cyclist approaches a safe following distance (2.02 meters in the current example) so that he/she keeps travelling at a reduced speed to maintain this distance. The average following distance was found to be 2.36 m, with a standard deviation of 0.50 m for the 65 interactions analyzed.

Table 3 shows the mean and the standard deviation of the cycling speed, and the walking speed during the following maneuver, compared to corresponding values during free moving periods. As shown in the table, the cycling speed was significantly reduced by about 39% when following slower pedestrians in the shared space. The pedestrian speed was almost constant during the maneuver, which was expected since pedestrians did not apply any evasive actions and, in
some cases, they were not even aware of the following cyclist.

Based on the previous analysis, it is suggested to define three parameters to model this type of interaction in a micro-simulation model:

1. The longitudinal distance between the pedestrian and the cyclist at which the cyclists start to reduce their speeds.
2. The desired distance, which the cyclists prefer to keep from slower leading pedestrians (following distance).
3. The cyclists’ deceleration needed to reduce speed when approaching the slow pedestrian.

b) Description of the Overtaking Strategy

Fourty interactions that involve an overtaking maneuver were observed in the analyzed data set. The maneuver typically includes cyclists changing their movement direction at a specific distance from the slower pedestrians to avoid collision. As well, an increase in cycling speed was observed during the overtaking phase. Figure 6 shows an example of a cyclist’s overtaking maneuver. The cyclists and pedestrians speed and acceleration profiles, and the longitudinal distance profile between the cyclist and the pedestrian are shown in Figure 7. As shown in the figure, this type of interaction can be described by the following three phases:

1. Phase 1: the cyclist is moving at the normal cycling speed (or at a reduced speed if the cycling is following a slower pedestrian as was noticed in many cases).
2. Phase 2: the cyclist decides to execute a swerving maneuver to overtake the slower pedestrian. This usually occurs when an adequate space becomes available for the cyclists to perform the maneuver. The cyclist accelerates and swerves in order to overtake the slower pedestrian. The average acceleration observed in the 40 interactions was found to be 0.87 m/s$^2$, with a standard deviation of 0.35 m/s$^2$. According to the data analyzed in this
study, the swerving maneuver is usually initiated simultaneously with the cyclist’s acceleration. The average longitudinal distance between the overtaking cyclists and the overtaken pedestrians at the start of the overtaking maneuver was found to be 3.00 m, with a standard deviation of 1.65 m.

3. Phase 3: the cyclist reaches the desired speed and the desired lateral distance that he/she prefers to keep from the slower pedestrian. Consequently, the cyclist maintained the desired speed and continues cycling in the original movement direction to overtake the slower pedestrian. The average minimum lateral distance between the overtaking cyclists and the overtaken pedestrians during the analyzed maneuvers was found to be 1.23 m, with a standard deviation of 0.25 m.

Table 3 shows the mean and the standard deviation of the cycling speed, and the walking speed during the overtaking maneuver, compared to corresponding values before the interaction. As shown in the table, the cycling speed increased significantly during the overtaking process. On average, cyclist speeds were increased by about 41% during the overtaking of the slower pedestrians in the shared space. Similar to the previous interaction, it was found that the pedestrian speed was almost constant during the maneuver, which was expected since pedestrians did not apply any evasive action and, in some cases, they were not even aware of the following cyclist.

Based on the previous analysis, it is suggested to define three parameters to model this type of interaction in a micro-simulation model:

1. The longitudinal distance between the cyclist and the pedestrian at which at the swerving maneuver starts.

2. The lateral distance between the overtaking cyclists and the overtaken pedestrians at the passing point.

3. The cyclists’ acceleration needed to execute the overtaking maneuver.
Interactions with Shared-Space Users Moving in Opposing Direction (Head-on Interactions)

This type of interaction occurs when a pedestrian and a cyclist approach each other, with an angle of 180° ± 30°, in time and space so that a collision would occur if none of them takes an evasive action. In the analyzed video data, sixty-two head-on interactions were observed. This type of interaction involves at least one of the shared-space users in conflict changing direction to avoid the collision. It was observed that cyclists tend to change direction when the shared space density is relatively low, where a sufficient lateral distance is available for bikes to perform the swerving maneuver. While at higher densities, pedestrians are more likely to take the evasive action. The average value of the shared space density and the available lateral space for road users during the swerving maneuver are presented in Table 4.

It was observed that most of the maneuvers are associated with a reduction in the cyclist’s speed. Table 5 shows the mean and the standard deviation of the cycling speed, and the walking speed in both free flow conditions and during the interaction. As shown in the table, cycling speed is reduced significantly during the interaction, regardless whether the cyclist executes a swerving maneuver or not. The average reduction in speed during the interaction was found to be 20%. On the other hand, the speed of pedestrians involved in this type of interaction did not change during the interaction regardless of whether they change the movement direction. This agrees with the results reported in (Hussein and Sayed 2015), which indicated that pedestrians do not change speed when changing direction to avoid an opposing pedestrian. However, other studies found that pedestrians may change their speed while changing the direction (Daamen et al. 2014). Figure 8 and Figure 9 show a typical example of a head-on interaction along with the corresponding speed and acceleration profiles of the two shared space users involved in the interaction. As shown in Figure 9, this type of interaction can be described by the following three phases:
1. Phase 1: cyclist is moving at the preferred speed, depending on the current density of the shared space environment.

2. Phase 2: the cyclist approaches the opposing pedestrian and decides to swerve and reduce speed to avoid collision. The average deceleration value for the cyclists was found to be 1.14 m/s$^2$, with a standard deviation of 0.75 m/s$^2$. The average longitudinal distance at which the cyclist or pedestrian starts to execute the evasive action was found to be about 6.39 m, with a standard deviation of 2.31 m.

3. Phase 3: once the cyclist ensures that he/she has an adequate lateral distance with the opposing pedestrian, the cyclist starts to accelerate to the normal cycling speed at the current density level of the shared space. The average acceleration value for the cyclists was found to be 1.11 m/s$^2$, with a standard deviation of 0.56 m/s$^2$. The average lateral distance between the cyclists and pedestrians at the crossing point was found to be 1.24 m, with a standard deviation of 0.32 m. This lateral distance is significantly higher than the corresponding distance in pedestrian head-on interactions. Hussein and Sayed reported that the average lateral distance between two opposing pedestrians on a typical crosswalk in Vancouver was 0.75 m (Hussein and Sayed 2017). The difference can be explained by the larger size and the higher speed of bicycles, compared to pedestrians.

Based on the previous analysis, it is suggested to define three parameters to model the head-on interaction between pedestrians and cyclists in a micro-simulation model:

1. The longitudinal distance between the cyclist and the pedestrian at which one of them starts to swerve to avoid the collision.

2. The lateral distance between the cyclists and the pedestrians at the crossing point.

3. The cyclists’ acceleration and deceleration needed to execute the overtaking maneuver.
**Bicycles Interaction with Crossing Pedestrians**

This type of interaction occurs when a pedestrian and a cyclist approach each other from the side in time and space so that a collision can occur if no action is taken by either of the shared-space users. The shared space does not provide a right of way for one user over the other. Rather, all users share the right-of-way so that it is not always clear which shared-space user should yield during these interactions. Forty-one cyclist-pedestrian crossing interactions were observed in the data set. At least one shared space user involved in this type of interaction changed the speed and/or the direction to avoid a collision. The 41 interactions were classified into two categories; 1) interactions where the pedestrian crosses first (cyclist yields to the pedestrian), and 2) interactions where the cyclist crosses first (pedestrian yields for the cyclist). If the cyclist yields to pedestrians, pedestrians tend to increase their walking speed to cross and clear the conflict area. As shown in Table 6, the pedestrian speed increased significantly during the interaction if the cyclist yields to the pedestrian. On average, the speed of pedestrians increased by 25.7% during the interaction. The cycling speed was reduced significantly by about 23.4% in order to provide right of way for the pedestrians. If the pedestrian yields to the cyclist, pedestrians reduce their walking speed. On average, pedestrians significantly reduced their speed by 63.5% in order to provide the right of way to the crossing bicycles. As well, the cyclist speed was reduced significantly during the interaction. The average reduction in cycling speed during the interaction was found to be 18.8%. Values reported in Table 6 suggest that cyclists tend to reduce speed when approaching a crossing pedestrian. However, the decision is made by the pedestrian whether to speed up and cross first or slow down and allow the cyclist to cross first. The decision of the pedestrian depends on the approaching bike speed as shown in Table 7, where the approaching speeds of cyclists are significantly higher for the cases where the pedestrian yields (bike cross first) compared to the cases where pedestrian crosses first. If the approaching cyclist speed is high, pedestrians prefer to
yield for the cyclist. Otherwise, the pedestrian accelerates to cross before the cyclists.

Figure 10 and Figure 11 show a typical example of a crossing interaction that involves a cyclist yields to the crossing pedestrian along with the corresponding speed and acceleration profiles of the two shared space users involved in the interaction. As shown in the figure, the interaction can be described by the following three phases:

1. **Phase 1**: the cyclist and pedestrian are moving at their preferred cycling and walking speeds, depending on the current density of the shared space environment.

2. **Phase 2**: the pedestrian decides to cross first. The pedestrian increases his/her walking speed to safely clear the conflict course. The cyclist decelerates in order to allow the pedestrian to cross the conflict course safely. The average deceleration of cyclists yielded to pedestrian was found to be $0.92 \text{ m/s}^2$, with a standard deviation of $0.42 \text{ m/s}^2$. While the average deceleration of the cyclists when the pedestrians yield to cyclists was found to be $1.21 \text{ m/s}^2$, with a standard deviation of $0.68 \text{ m/s}^2$. The average longitudinal distance between the cyclists and pedestrians along the crossing point at which the cyclist or pedestrian behavior starts to be affected by this interaction is about $5.95 \text{ m}$ with a standard deviation of $2.73 \text{ m}$. At the end of this phase, the pedestrian has safely crossed the conflict course.

3. **Phase 3**: as the pedestrian clears the conflict course, the cyclist starts to bike at a cycling speed that is suitable to the current density level of the shared space.

Based on the previous analysis, it is suggested to define three parameters to model the crossing interaction between pedestrians and cyclists in a micro-simulation model. However, a more detailed analysis for a larger data set is required to determine the factors that affect pedestrian’s decision to yield or to accelerate and cross first, and the factors that affect the change of road user directions. The three recommended parameters are summarized as follows:
1. The percentage of the change in pedestrian’s speed for the two possible evasive actions (pedestrian yields to bike or crosses first).

2. The longitudinal distance between the pedestrian and the cyclist along the crossing point at which they start to modify speed to resolve the conflict.

3. The cyclists’ deceleration as they approach the crossing pedestrian, for the two possible evasive actions.

CONCLUSION AND FUTURE RESEARCH

This study investigates the microscopic interaction behaviour of cyclists and pedestrians in a non-motorized shared space in Vancouver, British Columbia. Video data were collected at the Robson Square shared space in downtown Vancouver. Trajectories of cyclists and pedestrians involved in 208 interactions (416 trajectories) in the shared space area were extracted using computer vision algorithms. The extracted trajectories were used to define the speed and acceleration profiles of road users, longitudinal and lateral distances between road users during the different phases of the interactions. The study demonstrates the use of speed and acceleration profiles, and relative spatial profiles in describing the microscopic interaction behaviour between cyclists and pedestrians. The interactions between cyclists and pedestrians were categorized into three categories; [i] interactions with shared-space users moving in the same direction, [ii] interactions with shared-space users moving in opposing direction (head-on interactions), and [iii] bicycles interaction with crossing pedestrians. Different collision avoidance mechanisms were applied by the road users to avoid collision with other road users during the interactions. The collision avoidance mechanisms involved either a change in the movement direction or walking/cycling speed or both of them to avoid collision with other shared-space users. The results showed that the collision avoidance mechanisms adopted by road users depend on several factors including the shared space density and the space available for road users.
The results obtained in this study represent the basis for developing the behaviour rules required to model cyclist and pedestrian interactions in shared space areas. The study identifies several parameters that can be used to model the microscopic behaviour of cyclists and pedestrians in the microsimulation models. Table 8 summarizes the parameters that describe cyclist-pedestrian interactions in shared space areas and the values reported in the current study. Modeling road user interactions can be beneficial in evaluating the safety and the facility performance under various designs of shared space areas.

Limitations of the current work are mainly related to the sample size of the interactions analyzed. Thus, future research should consider investigating shared-space users’ interactions in different environments and layouts of shared space areas using larger datasets. Investigating the changes in pedestrian speed while changing direction in head-on interactions and the factors effecting the change of road user directions in crossing interactions are also important. As well, it is recommended to develop statistical models to describe some of the interaction behaviour discussed in this study. This includes developing a statistical model to predict which shared space user yield in crossing interactions. Also, a model that addresses which shared space user changes direction in head-on conflicts is required.

REFERENCES


Record: Journal of the Transportation Research Board, **2672**(35): 46-57.


List of Figures:

1. FIGURE 1 The data collection site (a) world image, (b) camera Image.
2. FIGURE 2 Trajectory extraction process, and speed, acceleration and relative distance profiles extraction.
3. FIGURE 3 Logit Model for the Selection of the Collision Avoidance Mechanism in the Same-Direction Interaction
4. FIGURE 4 Example of a typical following strategy by cyclists hindered by a slower pedestrian moving in the same direction.
5. FIGURE 5 Example of a typical following strategy by cyclists hindered by a slower pedestrian moving in the same direction expressed by the speed, acceleration and longitudinal distance profiles.
6. FIGURE 6 Example of a typical overtaking strategy by cyclists hindered by slower pedestrians moving in the same direction.
7. FIGURE 7 Example of a typical overtaking strategy by cyclists hindered by a slower pedestrian moving in the same direction expressed by the speed, acceleration, and longitudinal distance profiles.
8. FIGURE 8 Example of a typical head-on interaction between cyclists and pedestrians (opposing direction interaction).
9. FIGURE 9 Example of a typical head-on interaction between pedestrians and cyclists expressed by the speed and acceleration profiles.
10. FIGURE 10 Example of a typical crossing interaction between cyclists and pedestrians (case of the pedestrian crosses first).
11. FIGURE 11 Example of a typical crossing interaction between pedestrians and cyclists expressed by the speed and acceleration profiles (case of the pedestrian crosses first).
### TABLE 1 Logit Model for the Selection of the Collision Avoidance Mechanism (Same-Direction Interaction)

<table>
<thead>
<tr>
<th>Model</th>
<th>Model Parameter value</th>
<th>Value</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td></td>
<td>5.045</td>
<td>(0.09)</td>
</tr>
<tr>
<td>Dist (m)</td>
<td></td>
<td>2.504</td>
<td>(&lt;0.01)</td>
</tr>
<tr>
<td>Den (road user/m²)</td>
<td></td>
<td>-29.888</td>
<td>(&lt;0.01)</td>
</tr>
<tr>
<td>Goodness of fit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DF</td>
<td></td>
<td>102</td>
<td></td>
</tr>
<tr>
<td>R²</td>
<td></td>
<td>0.801</td>
<td></td>
</tr>
</tbody>
</table>

Note: Values in parentheses represent the p-value. 1 m = 3.28 ft.

Statistically significant (at 95% confidence level).
Table 2 Features Significance across different Collision Avoidance Strategies

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean [SD], Collision Avoidance Mechanism</th>
<th>Following Strategy</th>
<th>Overtaking Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max. Available Distance (m)</td>
<td>1.28 [0.65]</td>
<td></td>
<td>3.53$^a$ [1.58]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt;0.01)</td>
<td></td>
</tr>
<tr>
<td>Shared space Density (object/m²)</td>
<td>0.52 [0.16]</td>
<td></td>
<td>0.25$^a$ [0.10]</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(&lt;0.01)</td>
<td></td>
</tr>
</tbody>
</table>

Note: Values in parentheses represent the p-value of the t-test. SD = standard deviation. 1 m = 3.28 ft.

$^a$Statistically significant difference (at 95% confidence level) compared with the cell directly to the left.
TABLE 3 Features Significance for Cyclist and Pedestrians by Interaction

<table>
<thead>
<tr>
<th>Interaction Type</th>
<th>Road Users involved in interaction</th>
<th>Parameter</th>
<th>Mean [SD], Bikes change speed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Normal/Before interaction</td>
<td>During Interaction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Speed (m/s) [SD]</td>
<td></td>
</tr>
<tr>
<td>Following Strategy</td>
<td>Bikes</td>
<td>3.12 [0.74]</td>
<td>1.85 [0.45]</td>
</tr>
<tr>
<td>(n=65)</td>
<td>Ped</td>
<td>1.67 [0.36]</td>
<td>1.68 [0.39]</td>
</tr>
<tr>
<td></td>
<td>Walking Speed (m/s)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overtaking Strategy</td>
<td>Bikes</td>
<td>2.30 [1.10]</td>
<td>3.14 [0.63]</td>
</tr>
<tr>
<td>(n=40)</td>
<td>Ped</td>
<td>1.24 [0.69]</td>
<td>1.18 [0.67]</td>
</tr>
<tr>
<td></td>
<td>Walking Speed (m/s)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Values in parentheses represent the p-value of the t-test. SD = standard deviation. 1 m = 3.28 ft.

*Statistically significant difference (at 95% confidence level) compared with the cell directly to the left.
Table 4 Features Significance across Head-on Interaction Collision Avoidance Strategies

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean [SD], Bikes Swerve</th>
<th>Mean [SD], Bikes Not Swerve</th>
<th>Mean [SD], Pedestrians Swerve</th>
<th>Mean [SD], Pedestrians Not Swerve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared-Space Density (object/m²)</td>
<td>0.26 [0.10]</td>
<td>0.40a [0.12] (&lt;0.01)</td>
<td>0.35 [0.12]</td>
<td>0.23a [0.1] (&lt;0.01)</td>
</tr>
<tr>
<td>Max. Available lateral distance for Bikes (m)</td>
<td>2.17 [0.97]</td>
<td>1.07a [0.39] (&lt;0.01)</td>
<td>1.52 [0.76]</td>
<td>2.30a [1.13] (&lt;0.01)</td>
</tr>
<tr>
<td>Max. Available lateral distance for Pedestrians (m)</td>
<td>2.08 [1.02]</td>
<td>2.71a [1.45] (0.01)</td>
<td>2.50 [1.26]</td>
<td>1.93a [1.04] (0.01)</td>
</tr>
</tbody>
</table>

Note: Values in parentheses represent the p-value of the t-test. SD = standard deviation. 1 m = 3.28 ft.

*aStatistically significant difference (at 95% confidence level) compared with the cell directly to the left.
### TABLE 5 Features Significance across Cyclists and Pedestrians in Head-on Interaction

<table>
<thead>
<tr>
<th>Bicycle-Ped Interaction Type</th>
<th>Road Users involved in interaction</th>
<th>Parameter</th>
<th>Mean [SD], Bikes Swerve</th>
<th>Mean [SD], Ped Swerve</th>
<th>Mean [SD], Both Swerve</th>
<th>Mean [SD], Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction with Opposing flow (Head-on) (n=62)</td>
<td>Bikes</td>
<td>Speed (m/s)</td>
<td>3.70 [1.40]</td>
<td>2.98a [1.07]</td>
<td>3.00 [0.96]</td>
<td>2.86 [0.62]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>2.33a [0.68]</td>
<td>2.26a [0.71]</td>
<td>2.26 [0.71]</td>
</tr>
<tr>
<td></td>
<td>Ped</td>
<td>Walking Speed (m/s)</td>
<td>1.67 [0.43]</td>
<td>1.70 [0.48]</td>
<td>1.57 [0.41]</td>
<td>1.74 [0.31]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.57 [0.43]</td>
<td>1.78 [0.32]</td>
<td>1.78 [0.32]</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.66 [0.40]</td>
<td>1.68 [0.44]</td>
</tr>
</tbody>
</table>

Note: Values in parentheses represent the p-value of the t-test. SD = standard deviation. 1 m = 3.28 ft.

aStatistically significant difference (at 95% confidence level) compared with the cell directly to the left.
### TABLE 6 Features Significance across Cyclist and Pedestrians in Crossing Interaction

<table>
<thead>
<tr>
<th>Bicycle-Ped Interaction Type</th>
<th>Road Users involved in interaction</th>
<th>Parameter</th>
<th>Normal/Before Interaction</th>
<th>During Interaction</th>
<th>Normal/Before Interaction</th>
<th>During Interaction</th>
<th>Normal/Before Interaction</th>
<th>During Interaction</th>
<th>Normal/Before Interaction</th>
<th>During Interaction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction with crossing flow (n=41)</td>
<td>Bikes</td>
<td>Speed (m/s)</td>
<td>3.36</td>
<td>2.57&lt;sup&gt;b&lt;/sup&gt;</td>
<td>4.61</td>
<td>3.65&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.52</td>
<td>2.80&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.02</td>
<td>3.14&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Ped</td>
<td>Walking Speed (m/s)</td>
<td>1.32</td>
<td>1.67&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.40</td>
<td>0.51&lt;sup&gt;a&lt;/sup&gt;</td>
<td>1.24</td>
<td>0.98</td>
<td>1.37</td>
<td>1.07&lt;sup&gt;a&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

Note: Values in parentheses represent the p-value of the t-test. SD = standard deviation. 1 m = 3.28 ft.

<sup>a</sup>Statistically significant difference (at 95% confidence level) compared with the cell directly to the left.

<sup>b</sup>Statistically significant difference (at 95% confidence level) compared with the cell directly to the left.
### Table 7 Features Significance across Crossing Interaction

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Mean [SD], Bikes</th>
<th>Mean [SD], Pedestrians</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pedestrian Cross First</td>
<td>Bike Cross First</td>
</tr>
<tr>
<td>Approaching speed (m/s²)</td>
<td>3.36 [1.44]</td>
<td>4.61 [1.60] (0.01)</td>
</tr>
</tbody>
</table>

Note: Values in parentheses represent the p-value of the t-test. SD = standard deviation. 1 m = 3.28 ft.

*Statistically significant difference (at 95% confidence level) compared with the cell directly to the left.*
### TABLE 8 Parameters to Model Cyclist-Pedestrian Microscopic Interaction Behaviour

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Evasive action</th>
<th>Factors affecting choice of the evasive action</th>
<th>Parameters needed to model</th>
<th>Values obtained from the current study Mean [SD]</th>
</tr>
</thead>
</table>
| (1) Same direction movement interaction (following strategy) | • Changing Speed (cyclist) | • Available lateral distance for bike  
• Shared space density | 1. Longitudinal distance at start of reducing speed  
2. Following distance  
3. Cyclist deceleration profile | 4.46 [1.29] m  
2.36 [0.5] m  
0.81 [0.40] m/s² (average value) |
| (2) Same direction movement interaction (overtaking strategy) | • Changing movement direction (cyclist)  
• Changing speed (cyclist) | • Available lateral distance for bike  
• Shared space density | 1. Longitudinal distance at start of overtaking maneuver  
2. Lateral distance  
3. Cyclist acceleration profile | 3.00 [1.65] m  
1.23 [0.25] m  
0.87 [0.35] m/s² (average value) |
| (3) Opposing direction movement interaction (head-on interaction) | • Changing movement direction (cyclist or pedestrian or both)  
• Changing speed (cyclist) | • Shared space density  
• Available lateral distance for bike  
• Available lateral distance for pedestrians | 1. Longitudinal distance at start of interaction  
2. Lateral distance  
3. Cyclist deceleration profile  
4. Cyclist acceleration profile | 6.39 [2.31] m  
1.24 [0.32] m  
1.14 [0.75] m/s² (average value)  
1.11 [0.56] m/s² (average value) |
| (4) Interaction with Crossing road users | • Changing movement direction (cyclist or pedestrian or both)  
• Changing in cyclist speed  
• Changing in pedestrian walking speed | • Speed of the approaching bike | 1. Longitudinal distance at start of interaction  
2. Percentage change in pedestrian’s speed  
3. Cyclist deceleration profile | 5.95 [2.73] m  
Cyclist yield to Ped 25.7%  
Ped yield to cyclist -63.5%  
0.92 [0.42] m/s² (average value)  
1.21 [0.68] m/s² (average value) |
FIGURE 1 The data collection site (a) world image, (b) camera Image.

118×58mm (300 × 300 DPI)
FIGURE 2 Trajectory extraction process, and speed, acceleration and relative distance profiles extraction.

120x84mm (300 x 300 DPI)
FIGURE 3 Logit Model for the Selection of the Collision Avoidance Mechanism in the Same-Direction Interaction

112x84mm (300 x 300 DPI)
FIGURE 4 Example of a typical following strategy by cyclists hindered by a slower pedestrian moving in the same direction
FIGURE 5 Example of a typical following strategy by cyclists hindered by a slower pedestrian moving in the same direction expressed by the speed, acceleration and longitudinal distance profiles.

329x436mm (300 x 300 DPI)
FIGURE 6 Example of a typical overtaking strategy by cyclists hindered by slower pedestrians moving in the same direction.

354x157mm (300 x 300 DPI)
FIGURE 7 Example of a typical overtaking strategy by cyclists hindered by a slower pedestrian moving in the same direction expressed by the speed, acceleration, and longitudinal distance profiles.

329x437mm (300 x 300 DPI)
FIGURE 8 Example of a typical head-on interaction between cyclists and pedestrians (opposing direction interaction).

344x154mm (300 x 300 DPI)
FIGURE 9 Example of a typical head-on interaction between pedestrians and cyclists expressed by the speed and acceleration profiles.

329x258mm (300 x 300 DPI)
FIGURE 10 Example of a typical crossing interaction between cyclists and pedestrians (case of the pedestrian crosses first).

397x155mm (300 x 300 DPI)
FIGURE 11 Example of a typical crossing interaction between pedestrians and cyclists expressed by the speed and acceleration profiles (case of the pedestrian crosses first).