Analysis of Road User Behavior and Safety during New York City's Summer Streets Program

Mohamed Hussein, M.A.Sc.
Research Assistant, Department of Civil Engineering
The University of British Columbia
6250 Applied Science Lane
Vancouver, BC, Canada V6T 1Z4
Email: m.hussein@civil.ubc.ca

Bianca Popescu, B.Sc.
Research Assistant, Department of Civil Engineering
The University of British Columbia
6250 Applied Science Lane
Vancouver, BC, Canada V6T 1Z4
Email: Bianca.Popescu@civil.ubc.ca

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

Lee Kim
Transportation Planner
AKRF, Inc
440 Park Avenue South
New York, NY 10016
Email: lkim@akrf.com

(Word count: Abstract: 214; Manuscript: 4497; Tables:1,250; Figures: 1750)

Abstract

Automated computer vision video analysis techniques were used to analyze video data during the operation of New York City's Summer Streets Program at a major signalized intersection. The main objectives of this study were to: 1) diagnose pedestrian and cyclist safety issues during the "shared space" operation and 2) demonstrate the feasibility of the automatic extraction of road user (e.g. pedestrian, runner, rollerblader, or cyclist) data required for microscopic behavior analysis. Road users' speeds and pedestrian gait parameters (step frequency and step length) were automatically extracted and analyzed. The results show that pedestrian walking speed was highest during the Summer Street operation (1.49 ± 0.54 m/s) as they had more street space to use and slowest during normal operations (1.30 ± 0.22 m/s). Bike speeds were low during the Summer Streets event (3.62 ± 0.97 m/s), likely because of interaction with pedestrians, but increased during normal traffic operations. Pedestrians and cyclists moving in groups tended to be slower, confirming results found in previous studies. The safety analysis was conducted using traffic conflict techniques (TCT). It was observed that the lowest rate of conflicts between pedestrians and cyclists and between cyclists was found to be during Summer Streets operations. In addition, an analysis of spatial violations show that some road users were not observing traffic rules in the transition period after Summer Streets ceased to operate.

Introduction

Encouraging sustainable modes of transportation and exercise—such as walking, rollerblading, jogging and cycling—is important to build healthy and livable communities. Policies promoting non-motorized modes of travel and events encouraging active lifestyles is helpful in motivating users to shift from motorized transportation modes to other sustainable modes. Active transportation is a simple way to increase the physical activity level of the population, contributing to improvements to overall public health. However, transportation safety problems are a serious concern for vulnerable road users. Vulnerable road users, such as pedestrians and cyclists, are subject to higher safety risks and usually represent the highest share of fatal road collisions [1]. They have higher per-mile casualty rate than car travel, yet pose minimal risk to other road users. Overall, traffic casualty rates are found to decline as walking and cycling increase in a community because drivers are more cautious [2]. Safety experts study pedestrian and cyclist behaviors and develop appropriate techniques to diagnose pedestrian safety issues and recommend pedestrian safety improvements. To enhance the safety of vulnerable road users, it is necessary to develop an understanding of this behavior through developing better tools to study vulnerable road user behavior.

In August 2008, New York City initiated the Summer Streets program. This event opened Park Avenue from Brooklyn Bridge to Central Park (approximately 7 miles/11 km) to pedestrians, cyclists, rollerbladers, and joggers, and created vehicle-free streets on three consecutive Saturdays from 7AM to 1PM to promote sustainable forms of transportation. All activities at Summer Streets were provided free of charge and designed for people of all ages and ability to share the streets respectfully [3], creating a "shared space."

In this study, video data was collected at a busy signalized intersection in New York City (Park Avenue South and East 29th Street) on August 2nd, 2014 during three operating periods: the Summer Streets event, the transition period from Summer Streets to normal operation and the normal operation. The purpose of this data collection is to demonstrate an automated methodology to diagnose safety issues of non-motorized road users during a busy car-free "shared space" environment. The potential for automatic extraction of non-motorized road users' data required to understand their behavior was also examined. In the past few years, video data collection has been gaining wider acceptance as an effective and practical data collection method that avoids problems associated with manual data collection. Due to the significant advances in the computer vision field, it is possible to automatically and accurately detect and track road users. This automatically collected and analyzed data is more accurate than manually collected and analyzed data [4].

The main objectives of this study are:

1. Diagnose non-motorized road users' safety issues during Summer Streets' transition period and normal operation. Assess the road user safety issues at the location and identify factors contributing to them. Traffic conflict technique (TCT) [[5], [6]] was applied to assess vulnerable road user's safety during the three phases of operation at the study location. This approach overcome many shortcomings associated with traditional road safety analysis techniques that depend on collision data [5]. The analysis was conducted using an automated road safety analysis system [[7], [8], and [9]]. This system can detect, track and classify road users as well as measure the severity of conflicts for complex interaction.
2. Extract data of non-motorized road users, including pedestrians, joggers, cyclists and other users (such as rollerbladers). Traditionally, pedestrian and cyclist walking speed measurement and volume counts have been considered the most important data for behavior analysis. With the advancement of computer vision technology, studying the behavior of vulnerable road users becomes more efficient. The automated video-based system was used successfully in previous studies to automatically collect pedestrian crossing speeds and volume data [[10], [11]] and cyclist speeds and volume data [[12], [13]]. This study is unique in its analysis as it demonstrates the applicability of the system to collect pedestrian, rollerblader, joggers and cyclist data during a complex shared space urban environment. Furthermore, pedestrian gait parameters, such as step frequency and step length, were automatically extracted, which can be used to provide better understanding of pedestrian behavior.

Previous Work

Pedestrian and Cyclist Tracking

The detection and tracking of different road users is a significant application in computer vision technology. Compared to tracking vehicular traffic, tracking smaller road users (such as pedestrians) is more difficult because of various user sizes and their complex movements. Pedestrians, for example, are difficult to track due to their frequent change in direction and other road users can easily occlude them. Common problems with tracking cyclists and pedestrians also include global illumination variations, shadow handling, and multiple object tracking [14]. Different technologies are combined to increase the accuracy of pedestrian and cyclist tracking [[15], [16]]. Enzweiler et al. [17] and Bertozzi et al. [18] provide detailed reviews of different methods used to track and detect pedestrians. A detailed methodology for detecting, tracking and classifying bicycles from video scenes can also be found in [19] and [20]. A typical road user detection and tracking sequence starts with object detection, hypothesis generation, classification, and tracking.

Conflict Analysis

Recently, the TCT has been advocated as a promising approach of evaluating the safety of road users from a broader perspective than relying on collision data, which requires observing collisions for long periods of time. A traffic conflict is defined as "an observable situation in which two or more road users approach each other in space and time to such an extent that there is a risk of collision if their movements remain unchanged" [21]. The objective of the TCT is to observe and analyze the frequent traffic interactions and near misses between road users. The validity of using traffic conflicts in safety studies has been established through the investigating the relationship between conflicts and collisions in recent studies [[22], [23], and [24]]. There are a number of conflict indicators proposed to measure the severity of a traffic conflict. In this study, the Time-To-Collision (TTC) indicator was used, defined as "the time that remains until a collision between two road users would have occurred if the collision course and speed difference are maintained" [25].

Speed and Gait Parameters

Pedestrian and cyclist speed is considered an important parameter in understanding road user behavior. For pedestrians, previous studies focused on estimating pedestrian speeds to investigate the behavior of pedestrians in different walking environments [e.g., [26]]. In addition, the effect of different pedestrian attributes on walking speed (such as age, gender, and group size, among others) has been investigated in several studies. For example, it was found that single pedestrians have faster crossing speeds compared to pedestrians walking in groups [[26], [27]]. More recently, automated methods using computer vision techniques calculate speed to study pedestrian behavior [4]. There are gaps in the literature analyzing jogger and rollerblader speed, mainly due to the lack of data of these road users. For cyclists, speed and behavior analysis has been an active research topic recently, with cyclist speed being studied within different route configurations [12]. To overcome shortcomings in manual methods, automated video analysis has become increasingly common. One study using computer vision to analyze cyclist speed behavior found that group size, travel path, lane position and helmet usage affect the cycling mean speed [12].

Gait analysis has recently emerged as an important approach to understanding pedestrian behavior, analyzing pedestrian step length and frequency. Hediyeh et al. [4] conducted a study using computer vision techniques to collect pedestrian gait parameters and speed data. Results of the study showed that the step frequency and step length are influenced by factors such as crosswalk grade, pedestrian gender, age, and group size. Hussein et al. [11] used computer vision techniques to conduct a gait analysis showing that walking speed for a single pedestrian is faster than those who walk in groups, males walk faster than females with a longer step length and violators have higher walking speed, which was dependent on step length, not step frequency.

Shared Space

Encouraging the mixing of slower speed pedestrians and cyclists with higher speed vehicles in a "shared space" is a novel concept following previous objectives of separating vulnerable road users from vehicles. A "shared space" typically achieves this safely and efficiently by designing the road to reduce the dominance of vehicular traffic by promoting pedestrian and cycling activity while viewing the road as a "place," in addition to its transportation mobility and accessibility purpose. The theory of "shared space" requires multi-disciplinary professions to collaborate in the development of transportation corridors, which has been argued by many authors [e.g. [28], [29]]. There are gaps in the literature with regards to safety studies of "shared spaces." Kaparias et al. [30] used a behavior analysis technique instead of a conflict analysis technique to analyze the conduct of pedestrians and vehicles in "shared space," and found an increased confidence of pedestrians but an unchanged behavior in drivers. Cyclovia or Open Streets events have also become popular festivals, taking place in "shared space" streets around the world. More than 80 North American cities share their streets by offering regularly scheduled events drawing pedestrians and cyclists to enjoy car-free streets [31]. Studies have documented the positive effects of these events on physical activity, environment, social cohesion and businesses in the area [e.g., [32], [33]].

Methodology

Road Users' Trajectory Extraction

The detection of road users from a video and the extraction of their trajectories is achieved through an automated video processing system developed at the University of British Columbia [[7], [34]]. As shown in Figure 1, the procedure starts with the feature tracking step, in which discrete points (features) are tracked on moving objects in the video scene. The system relies on the Kanade-Lucas-Tomasi Feature Tracker algorithm to track moving features. The details of the feature tracking process could be found in [34]. Next, features are grouped based on their speeds, proximity and movement patterns to create one object. The position of each object is tracked frame by frame to produce the road user trajectory. These objects are classified into different road users, depending on the classification methodology as described in [35]. However, a vital component of the system is to relate the tracked trajectories in the video image coordinates to their actual positions in the real world. This is done by creating a mapping between the real world coordinated and the image space (camera calibration), which was described in details in [36].

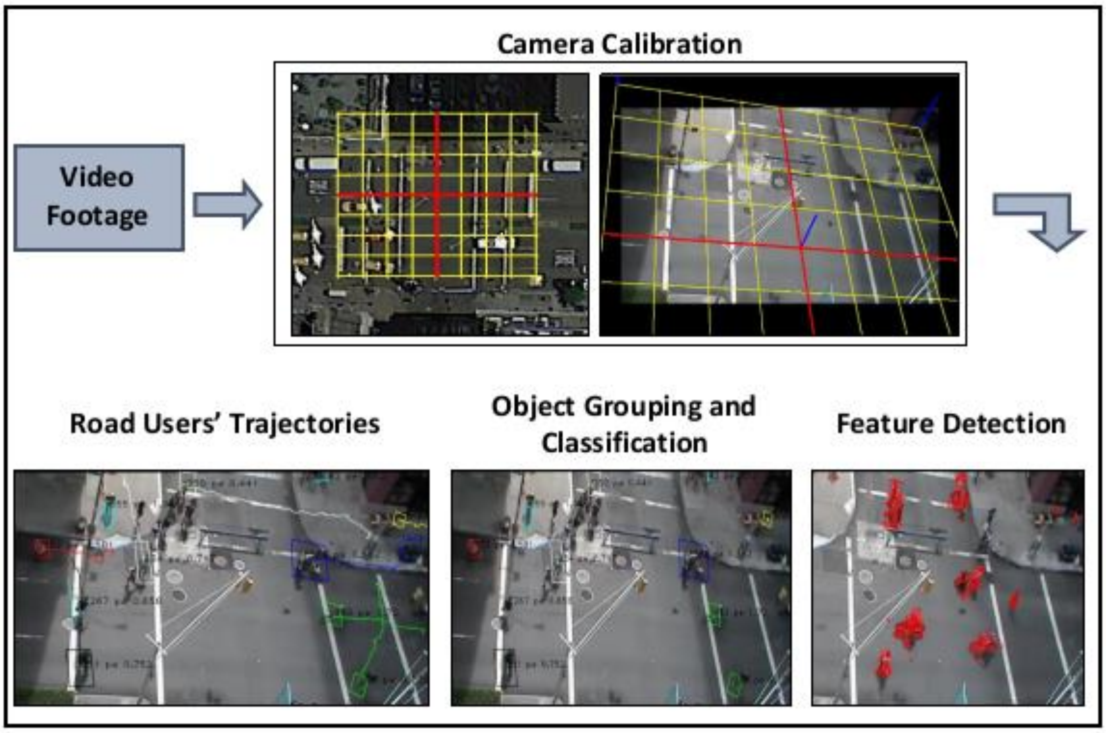


Figure 1. Trajectory Extraction Process

Conflict Analysis

The conflicts between road users in this study were extracted by predicting the future positions of each pair of road user trajectories and examining the probability of these predicted future positions to collide, in space and time, into one another [7]. Predicting the future positions of road users involve preparing a set of prototypical trajectories from previously learnt motion patterns of road users. Road user trajectories are then matched to these prototypes using the longest common sub-sequence algorithm (LCSS) to provide a set of predicted future positions with relative probabilities [8]. Typically, conflict indicators are used to measure the severity of the detected conflicts. This study used the TTC indicator as a measure of conflict severity. Only traffic conflicts with TTC less than 1.5 seconds was considered. TTC is calculated for each frame between conflicting road users until they are no longer on a collision course, and each conflict is associated with a set of TTC values. The minimum TTC is then used to represent the overall severity of the conflict. TTC is used for in this study for demonstration only. Other conflict indicators, such as Post Encroachment Time (PET), could also be used. This procedure of conflict analysis has previously been validated in [37].

Road Users' Speed and Pedestrian Gait Parameters Analysis

After a road user trajectory is extracted from the video scene, the road user speed profile can be easily produced. The average speed of any road user is estimated directly from the speed profile as the average speed through the lifetime of the trajectory. For the automatic extraction of pedestrian gait parameters, step frequency can be computed automatically by analyzing the speed profile of each pedestrian [38]. It was observed that a pedestrian speed profile typically shows cyclic fluctuations repeated continuously over time. Hediyeh, et al. [38] determined that each fluctuation in a given speed profile corresponds to a new step taken by the pedestrian. Based on these observations, the pedestrian speed profile can be seen as a time-series. Identifying the step frequency involves evaluating the power spectral density (PSD) [[1], [38]] of the speed signal to detect the dominant periodicity in the speed profile. Once the step frequency and walking speed of a pedestrian is determined, the average step length can be calculated from the fundamental linear relationship:

$$\text{Walking Speed} = \text{Step Frequency} \times \text{Step Length} \quad (1)$$

Data Collection and Study Location

Video data was collected from the intersection of Park Avenue South and East 29^{th} Street in New York City. The analyzed data could be classified into three phases: First, 30 minutes of data covering the Summer Streets operations where both intersecting streets were closed for motorized vehicles. The second phase covers the transition period starting from the moment the streets are reopen for traffic until road users adapt to the regular operation The transition period was estimated to be 15 minutes based on the observed road users' behavior in the video scene. Finally, the third phase covers 30 minutes of data of the regular operations of the intersection. During regular operations, Park Avenue South is a two-way north-south roadway with two moving lanes, a raised median, and a parking lane in each direction (total roadway width = 69 feet or 21.0 meters). East 29^{th} Street carries one-way westbound traffic (total roadway width approaching Park Avenue South North Bound = 30 feet or 9.1 meters). The intersection is controlled by a pre-timed signal (cycle length = 90 seconds). Data used in this study was collected on August 2nd, 2014, from 11:45 AM to 2:30 PM.

Summary of Findings

Road Users Count

Table 1 summarizes the count of different road users during each of the three phases considered for the analysis. Counts are reported per 15 minutes for consistency as the transition period was only 15 minutes.

Table 1: Road users count for each period

Road user	Count (Per 15 minutes)		
	Summer Streets	Transition period	Normal operation
Pedestrians	560	398	384
Bikes	230	83	29
Vehicles	0	161	236
Child, bike	10	0	0
Baby carriage	6	0	0
Rollerblade	6	1	0
Jogger	49	4	2

Road User Trajectories

Road user trajectories were extracted according to the methodology described earlier. Figure 2 shows the spatial distribution of the pedestrian and bicycle trajectories for each of the three time periods considered. As shown in the figure, pedestrians use the full width of Park Avenue during the summer street operation (Figure 2-a). After the summer street operation was terminated, pedestrians start to shift towards the crosswalks during the transition period until the spatial distribution of their trajectories get back to normal operation configuration (Figure 2-e). However, during the transition phase (Figure 2-c), many trajectories were observed in the middle of Park Avenue, which can be considered as a violation event. This indicates that the transition period represents a hazard to pedestrians as they are not fully aware that the summer street operation has ended, which may lead to serious conflicts with other motorized road users using the roadway. Similar situations were noticed for bikes despite the absence of bike infrastructure at the intersection. Cyclists ride their bikes along Park Avenue during Summer Street operation (Figure 2-b), then move to the right side of the road when the event is over (Figure 2-f). The problem again appears during the transition period, when many bikes are still using the full width of Park Avenue despite the presence of vehicles in the street. These observations show that the transition period is a time where vulnerable road users have a higher risk of being involved in serious conflicts with motorized road users due to their non-compliance to traffic regulations.

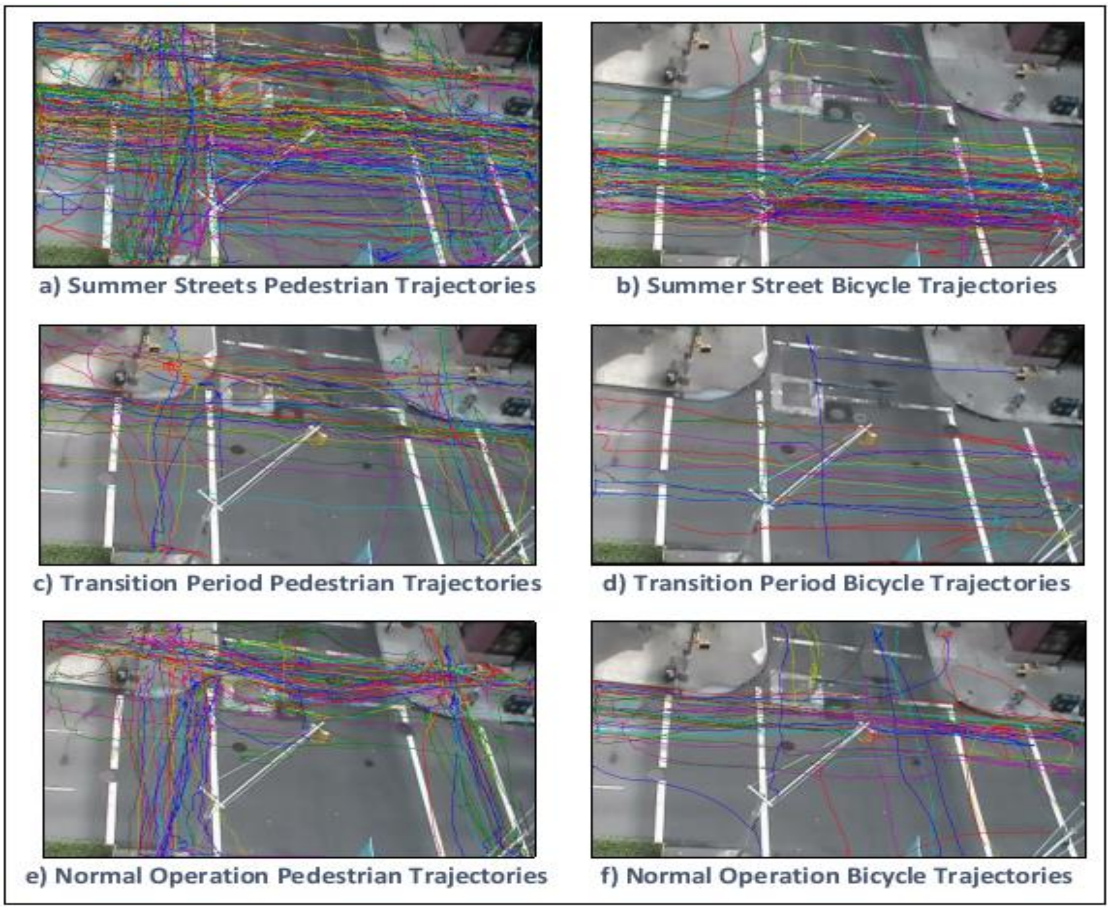


Figure 2. Spatial Distribution of Road Users' Trajectories

Traffic Conflicts

TCT was applied to investigate the frequency of serious interactions between different road users. Three conflict classes were extracted: conflict between bikes and pedestrians, conflicts between bikes and other bikes, and conflicts between motorized vehicles and all non-motorized road users. Extracted conflicts were classified among the three operational periods: Summer Street, transition period, and normal operation. Figure 3 shows the heat maps of automatically identified conflicts of the three classes considered while Table 2 summarizes the number of conflicts for each period and collision type.

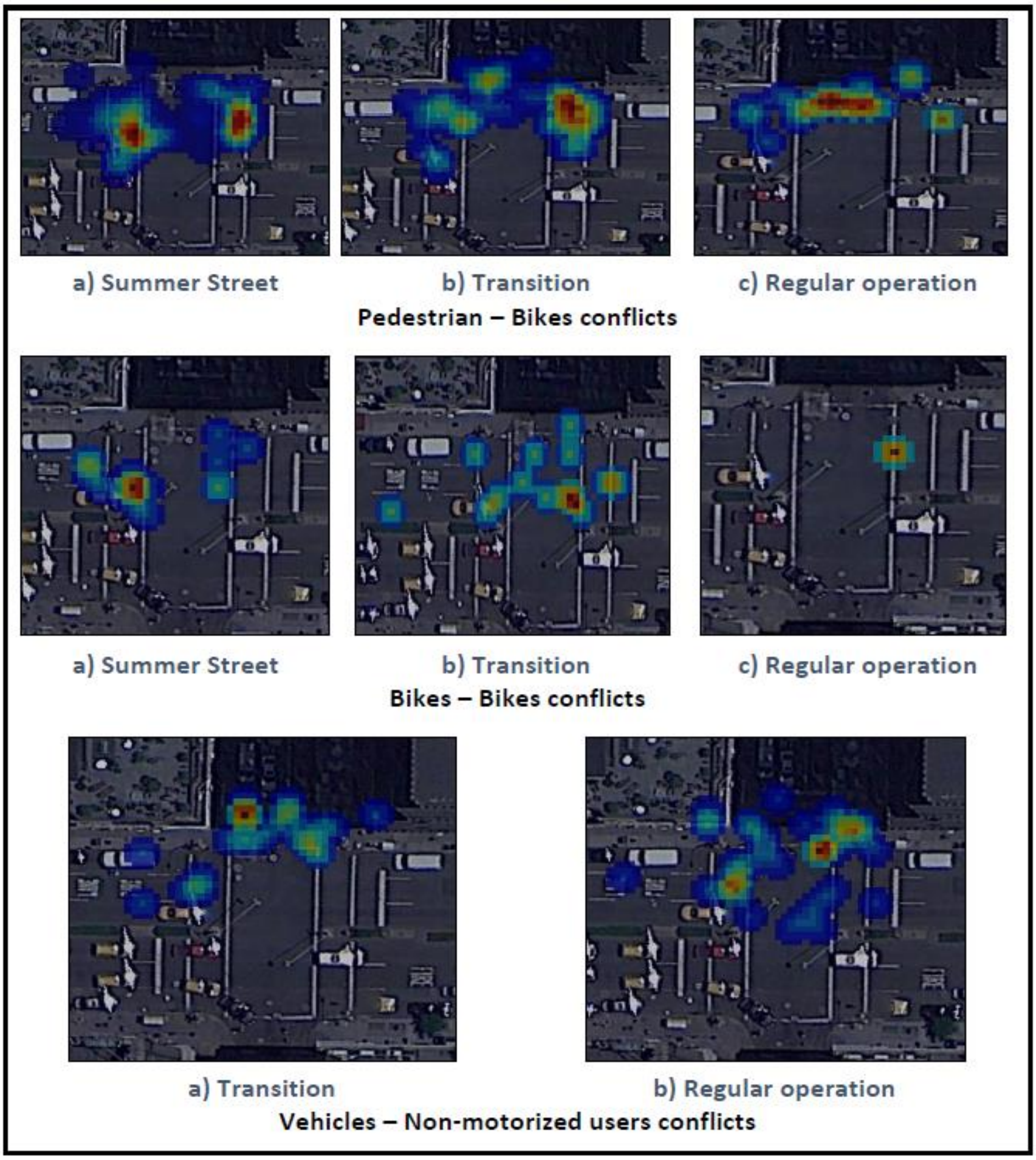


Figure 3. Heat Map of Road Users' Conflicts

Table 2: Number of TTC events for each period and collision type

Class	TTC events (Per 15 minutes)		
	Summer Street	Transition period	Normal operation
Pedestrian - Bike	127	59	26
Bike - Bike	16	14	1
Motorized Vehicle - Non motorized	4	24	43

The results show a large number of conflicts between pedestrians and bikes during the Summer Street period (127 conflicts/15 minutes) and these conflicts are spread almost over the whole study area as shown in Figure 3 (top left image) a. This large number of conflicts is difficult to compare since there are no published studies examining pedestrian–bicycle conflicts in a shared space environment. However, this large number of conflicts was expected because the

Summer Streets event drew a large number of pedestrians that used the full width of Park Avenue to walk. In addition, bikes have to navigate through the crowds creating many conflicts with pedestrians. The number of pedestrian–bicycle conflicts was reduced significantly in the transition period and the normal operation period afterwards. As well, conflicts began to concentrate around the crosswalks instead of the whole space, as it appears in Figure 3 (top right image). However, the relatively large number of conflicts in the transition period (59 conflicts in 15 minutes) and their spatial distribution (conflicts spread throughout the study space) suggests that the transition between Summer Streets and normal operation represent a hazardous period to road users as they are not yet complying to the traffic rules. This was the reason behind the presence of traffic police officers and traffic control agents to help direct traffic during the transition.

Conflicts between bikes were almost constant during the Summer Streets and transition periods despite the fact that the number of bikes during the transition period was significantly lower compared to during Summer Streets, as shown in Table 1. This suggests that the transition period reveals many road users' non-compliance to traffic rules, which lead to higher rates of conflict. It also shows that when organizing "shared space" events, the transition period should be carefully planned. The conflicts between bikes were not notable during normal operation due to the smaller number of bikes using the intersection during that period.

Conflicts between vehicles and non-motorized users were not expected during the Summer Streets period. However, a violation was observed during this period where a motorcycle passed through East 29th Street causing four conflicts with non-motorized road users (Figure 4). During the transition period, conflicts between motorized and non-motorized users mainly occurred at the east crosswalk (crossing East 29th Street), as shown in Figure 3 (the bottom left image). This is mainly because vehicles were allowed to move along East 29th Street for some time before Park Avenue was open for traffic. As such, many transitional period conflicts occur between the westbound traffic on East 29th Street and pedestrians and bikes on Park Avenue. The number of conflicts rises to 43 conflicts per 15 minutes during the normal operation phase, which is high and agrees with reported results [11] that intersections in New York City have high conflict rates between vehicles and non-motorized users.

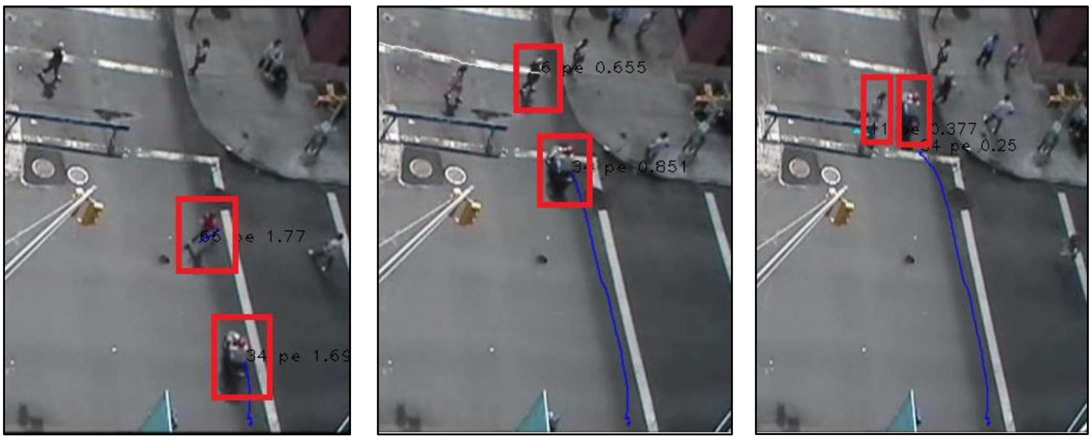


Figure 4. Motorbike Violation Event during Summer Streets and Associated Conflicts

Furthermore, as the number of road users varied significantly among the three periods analyzed, it is important to investigate the conflict rates in addition to the conflict frequencies discussed above. Figure 5 presents the different observed conflicts normalized by the number of conflicting road users of each category. Although the number of "pedestrian–bicycle" and "bicycle–bicycle" conflicts during the Summer Street period were significantly higher than the other two periods, the conflict rates were significantly lower. This indicates that the Summer Street period is the safest period for road users in terms of serious conflicts with other road users. Despite many interactions observed during Summer Streets, road users make use of the larger space available during Summer Streets where they can navigate freely and avoid serious conflicts, especially as their speeds are slower during this period as will discussed later. The "bicycle–bicycle" conflict rate recorded its peak during the transition period, which serves as confirmation of safety issues during the transition period. As well, although the conflict rates for "vehicle–non-motorized users" and "pedestrian–bicycle" conflicts were higher during the normal operation phase, the rates observed during the transition phase were still high and very close to those observed during the normal operation. The difference in observed rates between the two periods was about 24% and 28% for "pedestrian–bicycle" and "vehicle–non-motorized" conflicts, respectively, despite the presence of a police officer to regulate traffic during the transition period.

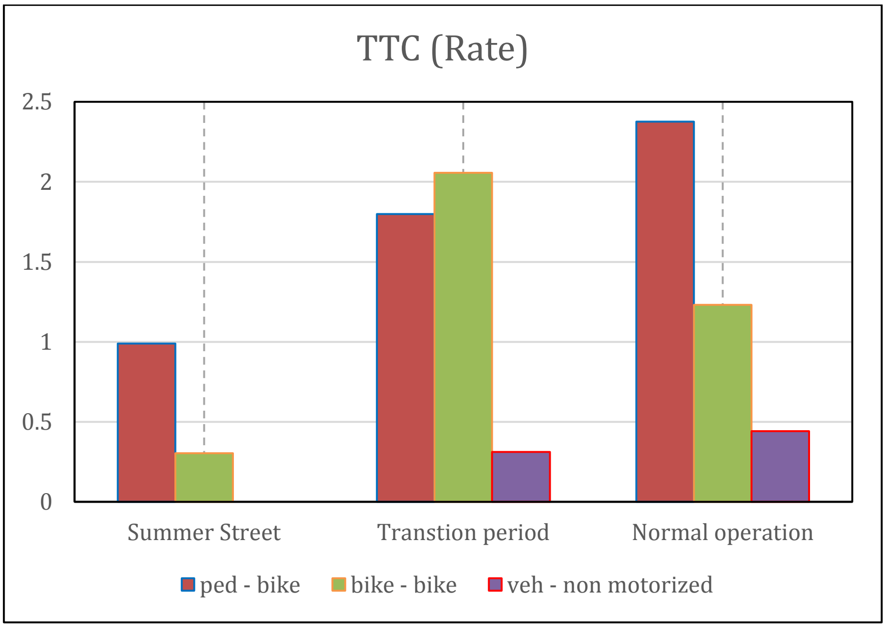


Figure 5. Conflict rates

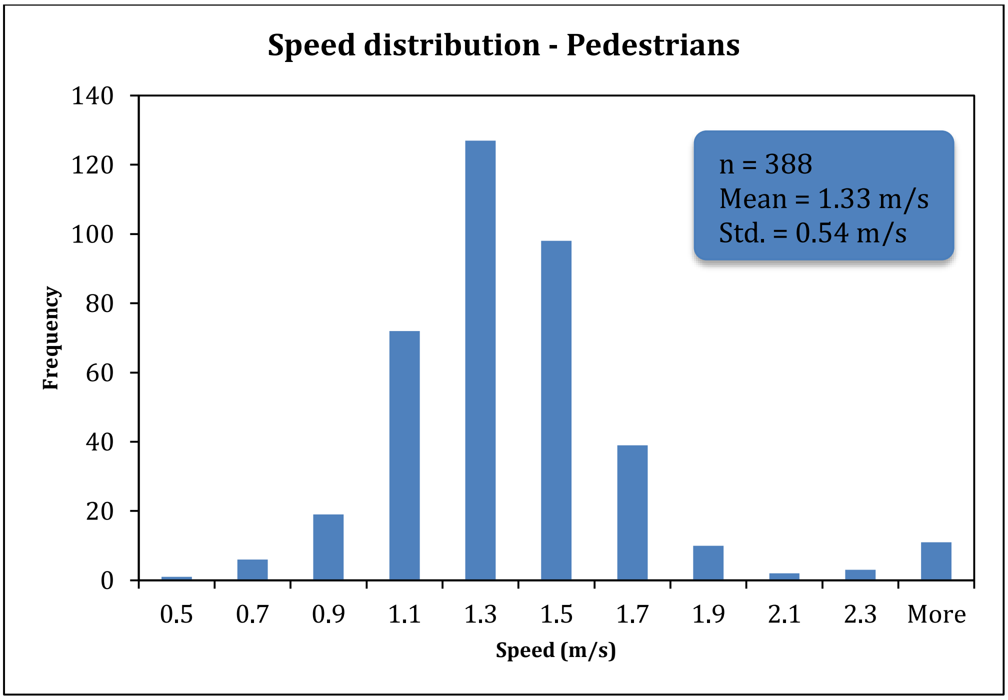
Road Users' Speed and Pedestrian Gait Analysis

Pedestrians and Joggers' Speed

Speeds of non-motorized road users (pedestrians, cyclists, joggers, and rollerbladers) were automatically extracted following the methodology described earlier. The distribution of both pedestrians' and joggers' speed is presented in figure 6. The mean and standard deviation for pedestrian and jogger speed was found to be (1.33 ± 0.54 m/s) and (2.81 ± 0.54 m/s), respectively. The variation of pedestrian speed during the three time periods of the festival was investigated. As shown in Table 3, pedestrians walked faster during the Summer Streets event and their speed reduced during the following periods. One hypothesis that can explain this is that they may be taking advantage of the “shared space” to move freely all over the width of the intersecting streets, while during the normal operation phase pedestrians have limited space (the sidewalks and crosswalks), which limit their speed, especially with the high density of pedestrians in the study location. Table 3 also shows the variation of pedestrian speed with group size. As shown in the table, the walking speed decreases as the group size increases which agrees with results reported in several previous studies [e.g., [11], [38], and [39]]. Unfortunately, the investigation of jogger’s speed variation during different phases and with group size was not possible, as joggers were only present during the Summer Street event and only ran individually.

Table 3: Summary of Pedestrian Speed

	Group Size			Analysis time			Total
	Single	Size = 2	Size = 3 +	Summer Streets	transition period	normal operations	
Count	148	174	**66**	220	58	92	388
Average speed (m/s)	1.38	1.33 (0.21)	**1.24 (0.10)***	1.49	1.39 (0.17)	1.30 (0.21)	1.33
Standard deviation (m/s)	0.58	0.54	**0.42**	0.74	0.73	0.47	0.54



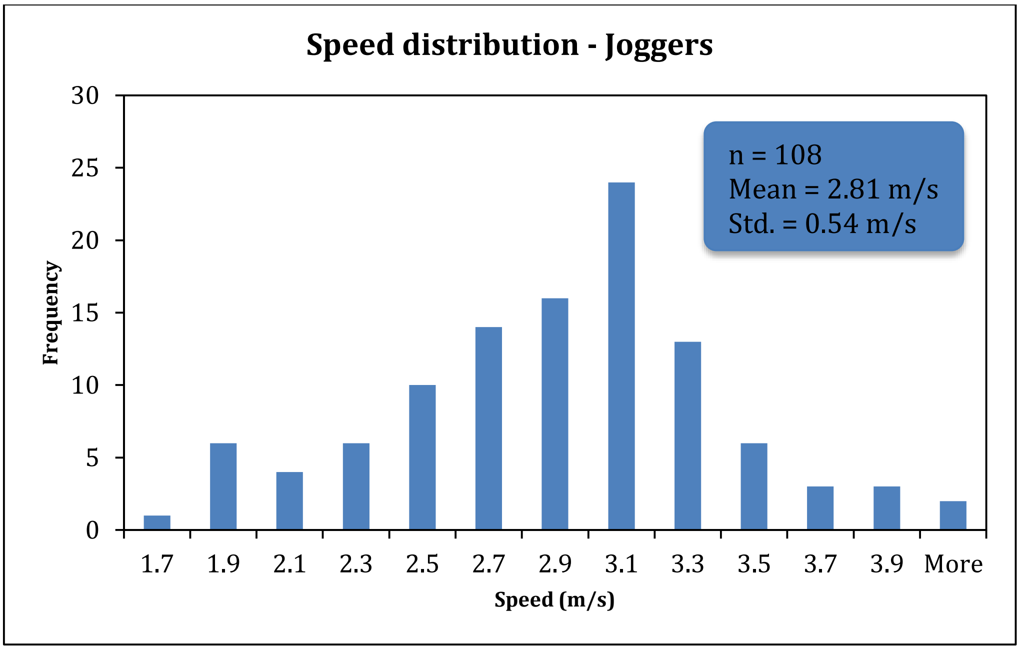


Figure 6. Speed distribution of pedestrian and joggers

Cyclists' Speed

The distribution of cyclists' speed is presented in figure 7. The mean and standard deviation for cyclists' speed was found to be (3.72 ± 1.04 m/s) with a minimum speed of 1.09 m/s and maximum speed of 8.30 m/s. The variation of cyclists' speed during the three time periods of the festival were investigated. As shown in Table 4, bike speeds were very low during the Summer Streets event and increased during normal traffic operations. These findings may be attributed to the "shared space" of Summer Streets attracting bikers of different ages to ride their bikes in a relaxed manner for leisure and consequently, the average biking speed is expected to be low. On the other hand, it is expected that during the normal operations, more cyclists use their bike to commute with higher speed. In addition, the presence of pedestrians in the street during the summer street event forces bikes to slow down to avoid collision with pedestrians and to navigate through the crowds. The effect of group size on biking speeds was also investigated. As was expected, when the cyclists' bike in groups, their speed on average becomes slower. Groups of cyclists were observed only during the Summer Streets operations, when the "shared space" allowed them to take the road and cycle at slower speeds in larger groups. Group cycling is common in bicycle-friendly cities where larger proportions of cyclists and separated bicycle infrastructure allow cyclists to feel safe and relaxed cycling in groups [40].

Table 4: Summary of Cyclist Speeds

	Group Size		**Analysis time**			
	Single Bike	**Size = 2+**	**Summer Streets**	**Transition Period**	**Normal Operations**	**Total**
Count	101	134	150	34	28	235
Average speed (m/s)	**3.93**	**3.56 ** (.01)**	3.62	3.86 (0.13)	4.17 (0.2)	3.72

Standard deviation (m/s)	1.43	0.79	0.97	1.17	1.57	1.04

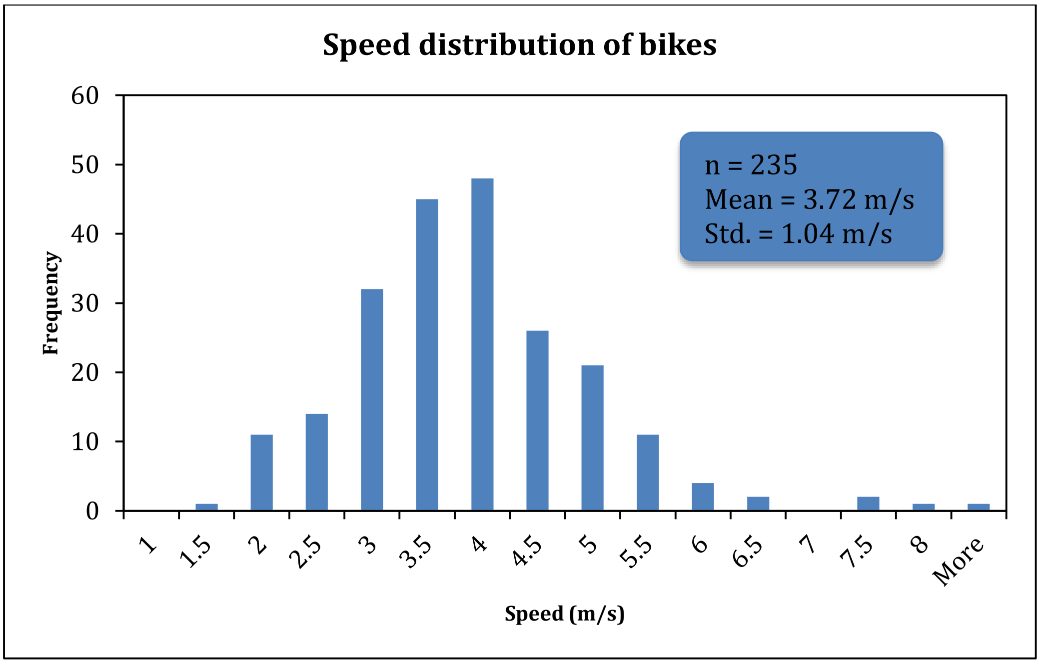


Figure 7. Speed distribution of bikes

Rollerbladers' Speed

The concept of Summer Streets encourages alternative road users, such as rollerbladers, to utilize and share the road. Although only 13 rollerbladers were observed during the analyzed data, we think it is worth reporting the values obtained as a reference. Further analysis on a larger data set is highly recommended. The average speed of rollerbladers was 3.13 m/s with a standard deviation of 0.69 m/s. The maximum rollerblader speed was 4.39 m/s and the minimum was 2.48 m/s.

Road users' speed compared to FHWA study

The speed of different road users during summer street operation were compared to the Federal Highway Administration's *Shared Use Path Level of Service Calculator* [41], presented in Table 5. It was observed that the average speeds for road users during Summer Streets operations are slower than the typical speeds for road users on shared paths. This is most likely because the festival encourages a larger group of people to enjoy "shared spaces" and road users may be slowing down to enjoy the Summer Streets.

Table 5: Comparison of road users' speed during Summer Street and values extracted from shared use path LOS calculator

Road User	Summer Streets average Speed (m/s)	Shared Use Path LOS Calculator average Speed (m/s)
Pedestrians	1.38	2.91
Bikes	3.93	5.72

Rollerbladers	3.13	4.52

Pedestrian Gait parameters

Pedestrian gait parameters (mainly, step frequency and step length) were automatically extracted and compared to the findings reported from the pedestrian gait analysis studied at Park Avenue South and East 28th Street during typical New York City street operations in [11]. The frequency and length parameters were found to follow the normal distribution with 95% confidence, as confirmed by the x^2 test. Step frequency and step length were found to be (1.8 ± 0.17 Hz) and (0.7 ± 0.116 m), respectively. Both the step frequency and lengths were smaller compared to values extracted from typical New York City street operations reported in [11] (reported step frequency in this study was 1.96 ± 0.17 Hz and step length was 0.75 ± 0.14 m). These differences are due to the fact that Summer Street data is collected on pedestrians in a "shared space" environment, while the New York City data is collected during peak hour normal operations. The "shared space" creating a sense of place on the street and the recreational nature of the festival is hypothesized as the reason for smaller pedestrian gait parameters during Summer Streets.

Conclusions and Future Research

Seventy-five minutes of video data were collected at a signalized intersection of Park Avenue South and East 29th Street in New York City during three different periods of operations: Summer Streets "shared space" operations, the transition period, and normal operations. Analysis was conducted on video data by means of computer vision techniques using an automated system developed at the University of British Columbia. The main purposes of the analysis are: 1) to assess pedestrian and cyclist safety issues at the intersection during the "shared space", transition, and normal operations and to identify factors that contribute to the safety issues; 2) to demonstrate the utility of the automatic extraction of pedestrian, cyclist, rollerblader, and runner data to better understand road user behavior, speed, and pedestrian gait parameters (step length and step frequency) during the "shared space," transition, and normal operations periods.

TCT were adopted to diagnose road user safety at the intersection during the three periods. The study identified pedestrian–bicycle, bicycle–bicycle, and vehicle–non-motorized conflicts during the Summer Streets operation, transition period, and normal operation time periods. Trajectories of pedestrians and cyclists show that the road users were not observing traffic rules in the transition period and normal operations, as they were spatially distributed through the street. The lowest rate of conflicts between pedestrians and cyclists and between cyclists was found to be during Summer Streets "share space" operations. It is hypothesized that this is due to cyclists slowing down because they do not need to compete with vehicle traffic, as well as the street being used recreationally during the festival. It is recommended that North American cities take the opportunity to implement "shared spaces" to create safer streets for vulnerable road users. Many European cities have examples of place-making and improving safety through implementing "shared spaces." In the meantime, open street festivals that close roads to vehicular traffic encourage sharing space, active lifestyles, and sustainable living.

Relatively large number of pedestrian–bicycle conflicts were observed in the transition period (59 conflicts in 15 minutes) and bicycle–bicycle conflicts (14 conflicts in 15 minutes) and their spatial distribution (conflicts spread throughout the study space) suggests that the transition between Summer Streets and normal operation represent a hazardous period to road users as they are not yet complying to the traffic rules. This shows that when organizing "shared space" events, the transition period should be given more thought.

In addition to conflict analysis, road user (pedestrian, runner, cyclist, and rollerblader) speeds and pedestrian step frequency and step length were automatically extracted. The parameters were found to follow the normal distribution with 95% confidence, as confirmed by the x^2 test. Comparing Summer Streets operations to typical New York City street operations, both the pedestrian step frequency and lengths were smaller. The "shared space" creates a sense of place on the street and recreational nature of the festival is hypothesized as the reason for smaller pedestrian gait parameters during Summer Streets. Results show that pedestrians were fastest during Summer Street operations (1.49 ± 0.54 m/s) and slowest during normal operations (1.30 ± 0.22 m/s). These results show that pedestrians may be taking advantage of the "shared space" festival to get exercise. The results for different pedestrian group sizes of singles, two pedestrians and three pedestrians were found to be (1.38 ± 0.34 m/s), (1.32 ± 0.30 m/s) and (1.24 ± 0.18 m/s), respectively, show that as group sizes become larger, pedestrians walk more slowly. This study was the first to automatically extract rollerblader speed and found it to be (3.12 ± 0.69 m/s), however due to small sample size (n=13), further analysis is recommended.

For cyclists, the results show that the "shared space" allowed them to cycle slower at speeds of (3.62 ± 0.95 m/s) than normal operations where cyclists traveled adjacent to vehicle traffic at speeds of (4.17 ± 2.46 m/s). The results also showed that as cyclist group sizes became larger, the cyclists on average were slower. Group cycling is common in bicycle-friendly cities with separate bicycle infrastructure, and it is a good indicator of a positive safety environment. This was the first study to automatically extract groups of cyclists, and further study on this topic is recommended.

Future work includes analyzing additional video data of "shared space" road user behavior and conflict analysis, calculating other conflict indicators (Post Encroachment Time, etc.), recommending specific safety countermeasures to design the optimal "shared space" and potentially conducting a before and after safety evaluation of the implemented "shared space." More data is required to come to any conclusions about the speed and behavior of rollerbladers, groups of pedestrians, and groups of cyclists. To better understand the safety and road user behavior of "shared spaces" it is important to analyze other similar environments—such as pedestrian-only streets, multi-use pathways, and Open Street events.

References

[1] Saunier, N., El Husseini, A., Ismail, K., Morency, C., Auberlet, J. M., & Sayed, T., "Estimation of frequency and length of pedestrian stride in urban environments with video sensors," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2264, no. 1, pp. 138-147, 2011.

[2] Victoria Transportation Institute, "Evaluating Active Transportation Benefits and Costs," 2014.

[3] New York City Department of Transportation, "Summer Streets," 2015. [Online]. Available: http://www.nyc.gov/html/dot/summerstreets/html/home/home.shtml.

[4] H. Hediyeh, T. Sayed and M. H. &. I. K. Zaki, "Automated analysis of pedestrian crossing speed behavior at scramble-phase signalized intersections using computer vision techniques," *International journal of sustainable transportation,* vol. 8, no. 5, pp. 382-397, 2014.

[5] T. Sayed and S. Zein, "Traffic Conflict Standards for Intersections," *Transportation Planning and Technology,* vol. 22, pp. 309-323, 1999.

[6] Chin, H. C., & Quek, S. T., "Measurement of traffic conflicts," *Safety Science,* vol. 26, no. 3, pp. 169-185, 1997.

[7] Saunier, N.; Sayed, T.; Ismail, K., "Large Scale Automated Analysis of Vehicle Interactions and Collisions," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2147, pp. 42-50, 2010.

[8] Saunier, Nicolas; Sayed, Tarek, "Automated Analysis of Road Safety with Video Data," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2019, pp. 57-64, 2007.

[9] J. Autey, T. Sayed and M. Zaki, "Safety Evaluation Of Right-turn Smart Channels Using Automated Traffic Conflict Analysis," *Accident Analysis and Prevention,* vol. 45, pp. 120-130, 2012.

[10] Zaki, M. H., Sayed, T., Tageldin, A., & Hussein, M., "Application of Computer Vision to Diagnosis of Pedestrian Safety Issues," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2393, no. 1, pp. 75-84, 2013.

[11] Hussein, M., Sayed, T., Reyad, P., & Kim L., "Automated pedestrian safety diagnosis and behavioral study at signalized intersections in New York City," *Transportation Research Record: Journal of the Transportation Research Board,* vol. In print, 2015.

[12] Zaki, M., Sayed, T., & Cheung, A., "Computer vision techniques for the automated collection of cyclist data," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2387, pp. 10-19, 2013.

[13] Sayed, T., Zaki, M. H., & Autey, J., "Automated safety diagnosis of vehicle–bicycle interactions using computer vision analysis," *Safety science,* vol. 59, pp. 163-172, 2013.

[14] B. Morris and M. Trivedi, "A Survey of Vision-Based Trajectory Learning and Analysis for Surveillance," *IEEE Transactions on Circuits and Systems for Video Technology,* vol. 18, no. 8, pp. 1114-1127, 2008.

[15] Curio, C.; Edelbrunner, J.; Kalinke, T.; Tzomakas, C.; Seelen, W. von, "Walking pedestrian recognition," in *IEEE/IEEJ/JSAI International Conference on Intelligent Transportation Systems*, 1999.

[16] Khanloo, B. Y. S., Stefanus, F., Ranjbar, M., Li, Z. N., Saunier, N., Sayed, T., & Mori, G., "A large margin framework for single camera offline tracking with hybrid cues," *Computer Vision and Image Understanding,* vol. 116, no. 6, pp. 676-689, 2012.

[17] M. Enzweiler and D. Gavrila, "Monocular Pedestrian Detection: Survey and Experiments," *IEEE Transactions on Pattern Analysis and Machine Intelligence,* vol. 31(12), pp. 2179-2195, 2009.

[18] Bertozzi, M.; Broggi, A.; Cellario, M.; Fascioli, A.; Lombardi, P.; Porta, M., "Artificial vision in road vehicles," *Proceedings of the IEEE,* vol. 90, no. 7, pp. 1258-1271, 2002.

[19] Buch, N., Orwell, J., & Velastin, S. A., "Urban road user detection and classification using 3D wire frame models," *IET Computer Vision,* vol. 4, no. 2, pp. 105-116, 2010.

[20] Cho, H., Rybski, P. E., & Zhang, W., "Vision-based bicyclist detection and tracking for intelligent vehicles," in *Intelligent Vehicles Symposium (IV), 2010 IEEE*, 2010.

[21] F. Amundsen and C. Hydén, "Proceedings of First Workshop on traffic Conflicts, Institute of Economics," in *Lund Institute of Technology*, Oslo, 1977.

[22] K. El-Basyouny and T. Sayed, "Safety performance functions using traffic conflicts," *Safety Science,* vol. 51, no. 1, pp. 160-164, 2013.

[23] Sacchi, E., Sayed, T., & deLeur, P., "A comparison of collision-based and conflict-based safety evaluations: The case of right-turn smart channels," *Accident Analysis & Prevention,* vol. 59, pp. 260-266, 2013.

[24] Zheng, L., Ismail, K., & Meng, X., "Shifted Gamma-Generalized Pareto Distribution model to map the safety continuum and estimate crashes," *Safety Science,* vol. 64, pp. 155-162, 2014.

[25] J. Hayward, "Near-miss determination through use of a scale of danger," *Highway Research Record,* vol. 384, pp. 24-34, 1968.

[26] Knoblauch, R. L., Pietrucha, M. T., & Nitzburg, M., "Field studies of pedestrian walking speed and start-up time," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 1538, no. 1, pp. 27-38, 1996.

[27] Gates, T. J., Noyce, D. A., Bill, A. R., & Van Ee, N., "Recommended walking speeds for timing of pedestrian clearance intervals based on characteristics of the pedestrian population," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 1982, no. 1, pp. 38-47, 2006.

[28] J. Jacobs, The death and life of great American cities, Vintage, 1961.

[29] Appleyard, D., Gerson, M. S., & Lintell, M., "Livable streets, protected neighborhoods," University of California Press, 1981.

[30] Kaparias, I., Bell, M. G. H., Biagioli, T., Bellezza, L., & Mount, B., "Behavioural analysis of interactions between pedestrians and vehicles in street designs with elements of shared space," *Transportation Research Part F: Traffic Psychology and Behaviour,* vol. 30, pp. 115-127, 2015.

[31] E. Beard, "Care-Free, Carefree Streets," Parks & Recreation, 2013.

[32] Engelberg, J. K., Carlson, J. A., Black, M. L., Ryan, S., & Sallis, J. F., "Ciclovía participation and impacts in San Diego, CA: The first CicloSDias," *Preventive medicine,* vol. 69, pp. S66-S73, 2014.

[33] Hipp, J. A., Eyler, A. A., Zieff, S. G., & Samuelson, M. A., "Taking physical activity to the streets: the popularity of Ciclovia and Open Streets initiatives in the United States," *American Journal of Health Promotion,* vol. 28, no. sp3, pp. S114-S115, 2014.

[34] N. Saunier and T. Sayed, "A Feature-Based Tracking Algorithm for Vehicles in Intersections," in *Third Canadian Conference on Computer and Robot Vision, IEEE*, Québec, 2006.

[35] Zaki, M. H. & Sayed, T., "A framework for automated road-users classification using movement trajectories," *Transportation Research Part C: Emerging Technologies,* vol. 33, pp. 50-73, 2013.

[36] Ismail, K., Sayed, T., & Saunier, N., "A methodology for precise camera calibration for data collection applications in urban traffic scenes," *Canadian Journal of Civil Engineering,* vol. 40, no. 1, pp. 57-67, 2013.

[37] Ismail, K.; Sayed, S. & Saunier, N., "Automated Analysis Of Pedestrian-vehicle Conflicts: A Context For Before-and-after Studies.," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2198, pp. 52-64, 2010.

[38] Hediyeh, H., Sayed, T., Zaki, M. H., & Mori, G., "Pedestrian gait analysis using automated computer vision techniques," *Transportmetrica A: Transport Science,* vol. 10, no. 3, pp. 214-232, 2014.

[39] Li, S., Sayed, T., Zaki, M. H., Mori, G., Stefanus, F., Khanloo, B., & Saunier, N., "Automated Collection of Pedestrian Data Through Computer Vision Techniques," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2299, no. 1, pp. 121-127, 2012.

[40] Aldred, R., and Jungnickel, K., "Constructing mobile places between 'leisure'and 'transport': a case study of two group cycle rides," *Sociology,* vol. 46, no. 3, pp. 523-539, 2012.

[41] Patten, R. S., Schneider, R. J., Toole, J. L., Hummer, J. E., & Rouphail, N. M. , "Shared-Use Path Level of Service Calculator—A User's Guide," (No. FHWA-HRT-05-138), 2006.

[42] Bain, L., Gray, B., & Rodgers, D., Living streets: Strategies for crafting public space, John Wiley & Sons, 2012.