MULTIMODAL SAFETY ASSESSMENT OF AN URBAN INTERSECTION BY VIDEO ANALYSIS OF BICYCLE, PEDESTRIAN, AND MOTOR VEHICLE TRAFFIC CONFLICTS AND VIOLATIONS

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ABSTRACT

This paper demonstrates the diagnosis of bicycle safety issues and evaluation of proposed improvements at a major intersection in Vancouver, British Columbia using automated traffic conflict analysis. Traditional road safety analysis has often been conducted using historical collision records. However, limitations associated with collision data have motivated the development of complementary proactive techniques for road safety analysis. Recently, there has been significant interest in using traffic conflicts to analyze safety which has been strengthened by the availability of automated traffic conflict analysis tools. Automated computer vision techniques are used to extract and analyze traffic conflicts from video data. Traffic conflict indicators, such as time to collision and post-encroachment time, are used to identify safety issues based on the frequency and severity of conflicts. Spatial and temporal non-conforming behavior patterns are also analyzed. The intersection safety diagnosis reveals that the main sources of bicycle and motor vehicle conflicts are associated with failure to yield at bicycle crossings of on- and off-ramps, and vehicle red-light and stop-bar violations. A new intersection design is evaluated for its expected ability to address the identified safety issues.

1 Introduction

Road collisions are the world's leading cause of preventable death: over 1.25 million people die every year on the roads because of traffic collisions, and traffic injuries have become the number one cause of death among people aged between 15 and 19 years old [1]. By some measures active transportation users such as cyclists are subject to higher safety risks than other road users, due to vulnerability in a collision [2]. As urban communities increasingly encourage cycling as a mode of transportation, the need for safer infrastructure grows.

Road safety diagnoses are used to identify factors that decrease safety at a location of concern [3]. Traditionally, road safety diagnoses have often been conducted using historical collision records. However, limitations associated with lack of detailed and accurate collision data and infrequent collision occurrence have motivated the development of complementary proactive techniques for road safety analysis [4-6]. Recently, there has been significant interest in using traffic conflicts as surrogates for collisions to analyze safety. Traffic conflicts can provide detailed information about the dynamics of road user interactions as it allows the analyst to observe the series of events that lead to a collision, providing a more comprehensive analysis than when using collision data alone [4]. Traffic conflict analysis can be complemented by the study of traffic violations (i.e. non-conforming behavior). Detecting and understanding non-conforming behavior can be beneficial in identifying movement patterns or flawed design elements that may be causing safety deficiencies [7]. The introduction of computer vision systems has strengthened traffic conflict and violation analysis by automating the extraction of accurate and detailed road user movement data, overcoming many of the shortcomings of manual traffic conflict techniques [8].

The objective of this research is to demonstrate the capabilities of computer vision-based multimodal safety evaluations, particularly for assessment of proposed bicycle safety improvements at a major urban intersection with safety issues. Bicycle, pedestrian, and motor vehicle conflicts and non-conforming behavior are analyzed to identify safety issues, and to assess the effectiveness of proposed safety improvements at the intersection. The safety diagnosis will also serve as the *before* analysis in a before-and-after study to be completed once the proposed improvements have been implemented.

2 Literature review

2.1 Traffic conflict techniques

A traffic conflict or near-miss 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 remained unchanged” [9]. Using traffic conflicts as a surrogate for traffic collisions helps to overcome several challenges in collision-based safety evaluations, such as statistical problems arising from the lack of precision in collision databases, infrequent collision occurrence, and small size of collision sample statistics [4-5]. However, the usability, reliability, and validity of traditional manual traffic conflict techniques have been challenged and are a source of concern among researchers [5, 10-11]. Quantitative, objective traffic conflict indicators such as “time to collision” (TTC, the time until a collision would occur if two conflicting road users were to continue on the same path and speed) and “post-encroachment time” (PET, the time difference between when one road user passes out of an area of possible collision and when the conflicting road user arrives at the same area) can help to overcome the subjectivity limitations of traditional manual traffic conflict analysis [12-13].

2.2 Non-conforming behavior

Road safety can be improved by correcting non-conforming behavior patterns (i.e. traffic violations) [14], and traffic violations can be used as surrogate measures of road safety in cases where collisions and conflicts are assumed to be attributable to non-conforming behavior [15]. Traffic violations occur when a road user disobeys traffic regulations, which may happen consciously by seeking an increase in mobility or unconsciously by ignorance of traffic regulations [16]. A study on driver behavior at bicycle crossings suggested that safety is often related to signage compliance, intersection configuration, yielding behavior, and vehicle speed [17]. Cyclist non-conforming behavior factors contributing to vehicle-bicycle collisions include not using hand gestures to announce intentions, performing abrupt or sudden maneuvers in proximity of vehicles, and failing to identify vehicles in the cyclist’s proximity [18]. For all travel modes, traffic violations are related to both personal and environmental factors [19-22].

2.3 Computer vision systems

Computer vision systems integrate processes and representations used for video perception to support automated and semi-automated data collection and traffic conflict studies [23]. Semi-automated methods use image processing tools to support manual tracking of road users [24-25], which can be labor-intensive for large samples. Automated methods can include road user tracking and classification based on location, movement, and attributes [26]. Despite the relatively high costs of equipment acquisition, analyst training, and implementation, costs and efforts associated with data collection can be substantially reduced with automated computer vision systems [15].

Computer vision techniques for traffic conflict analysis have been the subject of extensive work in recent years [3, 8, 27-29]. Computer vision techniques reduce the effects of observer subjectivity by extracting TTC and PET values from video data in an automated manner [16]. Furthermore, computer vision systems have been successfully applied to several types of traffic violations, including red-light running, lane-crossing violations, stop-line violations, speed violations, and non-yielding [3, 30-32].

3 Methodology

3.1 Study location

The study location is the intersection of Burrard Street and Pacific Street in central Vancouver, British Columbia (Figure 1). This intersection is at the north end of the Burrard Bridge and includes its access and egress ramps (hereafter referred to as “On-ramp” and “Off-ramp”, respectively). A two-phase signal system controls the intersection and there are four approaches: Burrard St. northbound (NB) and southbound (SB) and Pacific St. eastbound (EB) and westbound (WB). Only the WB approach allows for turns at the intersection. The On-ramp allows motor vehicles coming from the EB approach to turn right into the Burrard St. SB traffic flow, while the Off-ramp allows motor vehicles coming from the Burrard Bridge (Burrard St. NB approach) to turn right into the Pacific St. EB traffic flow. Due to the presence of the ramps, two traffic islands are created: one at the west side and one at the east side of Burrard St. (hereafter referred to as "West traffic island" and "East traffic island", respectively).

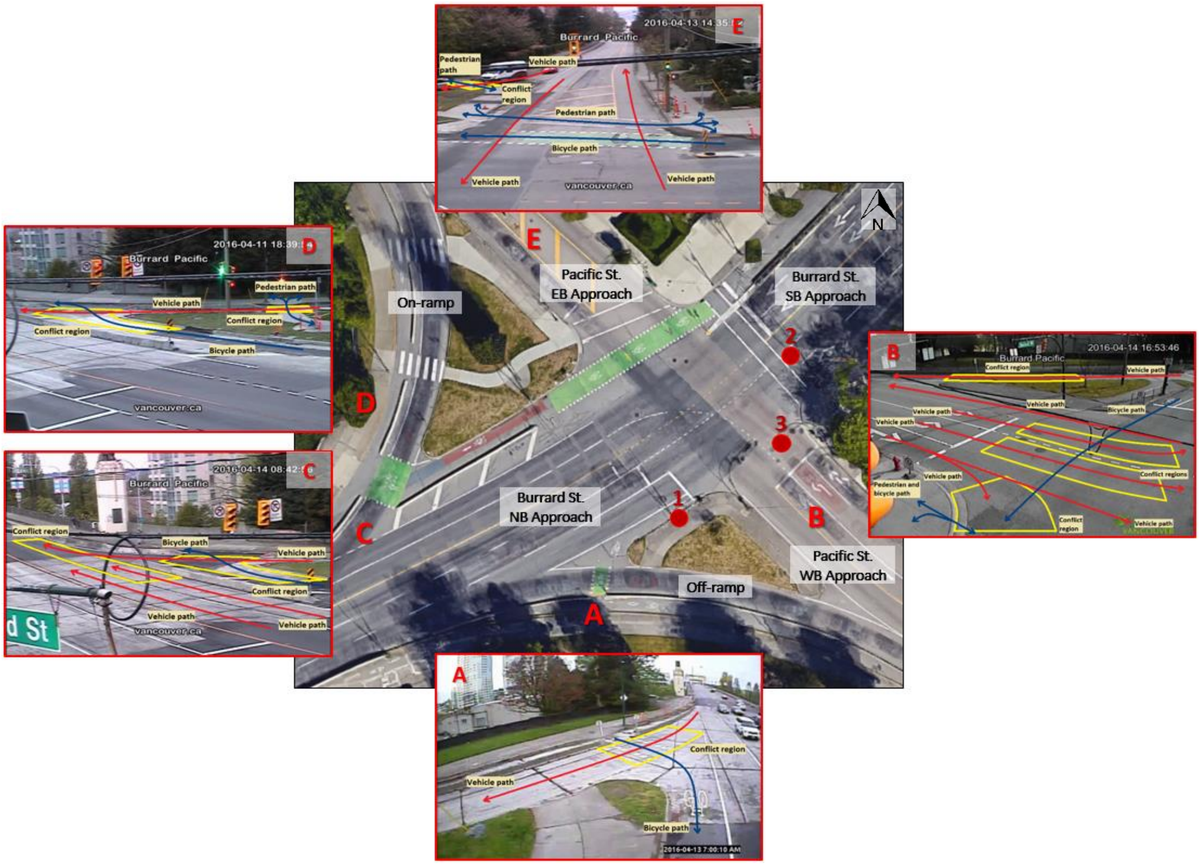

Figure 1: Study location, Burrard St. and Pacific St. intersection, with five scenes of video data collection.

The Burrard St. and Pacific St. intersection is part of Vancouver's Cycling Network [33] and services high bicycle volumes, with a daily average of 4,700 cyclists crossing the Burrard Bridge during the data collection period (April 2016) [34]. The Off-ramp has a sidewalk and a one-way protected bike lane with access to an exclusive bicycle crossing, allowing cyclists to cross through the Off-ramp and proceed across the Pacific St. WB approach. Pedestrians are not allowed to cross the Off-ramp nor the NB or WB approaches, so the East traffic island should not be used by pedestrians. The On-ramp has a bicycle crossing for the Burrard St. southbound-only bike lane and two crosswalks to the West traffic island (hereafter referred to as "North crosswalk" and "South crosswalk").

3.2 Video data and analysis

The City of Vancouver provided 53.4 hours of video footage recorded intermittently April 11-15, 2016 (expected to be typical non-holiday weekdays during school session). Video data extent is presented in Table 1. Five scenes (indicated A, B, C, D, and E in Figure 1) were recorded from three different cameras attached to the top of traffic signals (indicated 1, 2, and 3 in Figure 1). The SB approach could not be observed from any of the scenes, and the NB approach was partially occluded by power cables, so the NB and SB approaches are not included in the analysis.

Table 1: Video recording information.

Camera	Scene	Date	Start time	Finish time
1	A	April 13, 2016	07:00	19:00
2	B	April 13, 2016	08:52	19:00
3	C	April 15, 2016	08:04	19:00
3	D	April 11, 2016	08:07	12:25
			14:06	19:00
3	E	April 13, 2016	07:52	19:00

The video analysis process is illustrated in Figure 2. Camera calibration was used to convert the video-based two-dimensional information into three-dimensional spatial data, by annotating and cross-referencing points, distances, and angles in the camera image and an orthographic image of the study location. A calibration grid was also developed to perform a visual validation of the calibration accuracy. Details of the mixed-feature camera calibration process used can be found in [35].

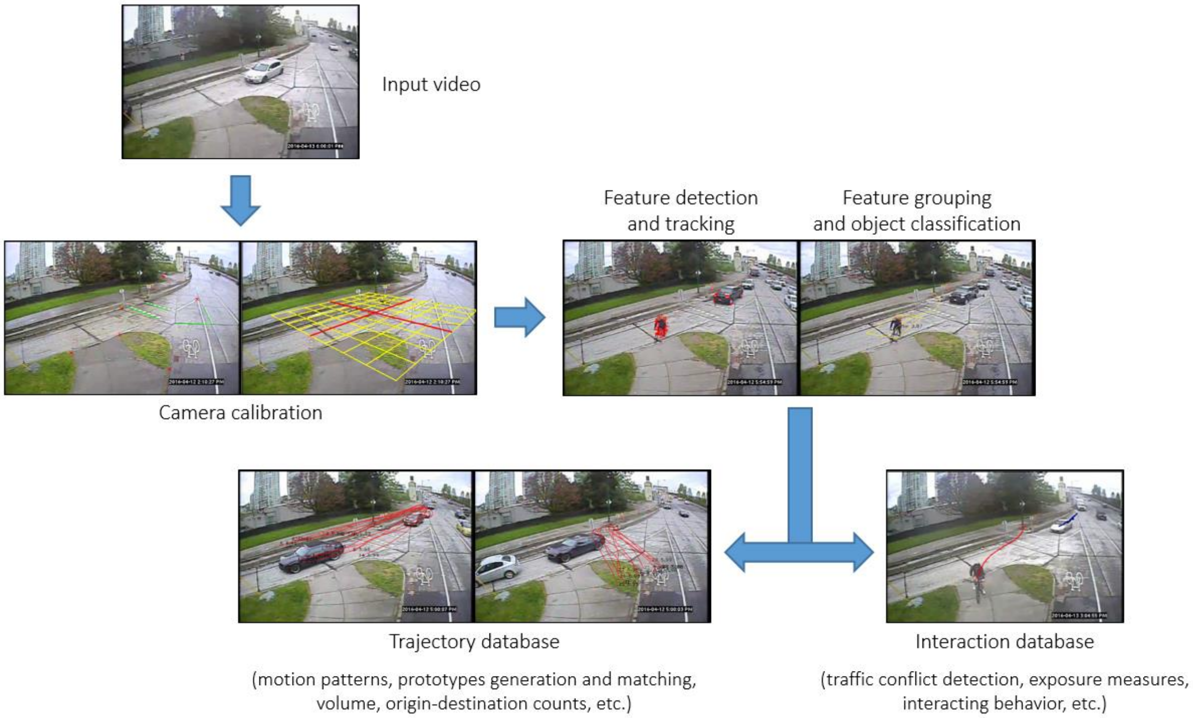

Figure 2: Video analysis process (using Scene A as an example).

After camera calibration, road users were tracked and classified. Feature tracking is the automated detection and tracking of features of road users as they navigate through the camera's field of view. The Kanade-Lucas-Tomasi feature-tracking algorithm [36] was used to differentiate between features that belong to road users and those that belong to the environment. Fixed objects were filtered by removing those features that remain stationary and are assumed to be part of the environment [37]. To optimize feature tracking, features were continually generated and motion checks performed to identify features with unreasonable motion properties. Because single objects generate multiple tracked features, the next step was object identification through feature grouping. Features were grouped if they were within a set distance apart and had identical motion patters in terms of speed and direction. Finally, objects were classified as motor vehicles, bicycles, or pedestrians based on their trajectories and speed profiles, as in [38]. More information on data collection using computer vision systems can be found in [39].

3.3 Traffic conflict and violation analysis

The detected trajectory and speed of each object was matched to a prototype (i.e. group of motion patterns that define the set of movements carried out by road users) using the Longest Common Sub-Sequence (LCSS) algorithm with a maximum LCSS matching distance [15-16]. Thus, a set of predicted future positions was determined for each object with associated probabilities of occurrence, and potential conflicts between road users was determined by evaluating if any of their future positions coincide in space and time [40]. The automatically-identified conflicts were also manually reviewed to filter tracking errors, such as over-segmentation (more than one track is attributed to a single road user), over-grouping (several road users are tracked together as a single object), and misdetection (a single road user is not detected). Traffic conflict indicators (TTC and PET) were used to measure the severity of each conflict. The minimum TTC during an interaction between two road users was used to represent the overall severity of the conflict.

Motor vehicle, bicycle, and pedestrian temporal and spatial violations were identified automatically for non-yielding and speeding [3], and manually for other types of violations. Temporal violations were assessed manually because synchronous signal phase data were not available.

4 Results

4.1 Intersection safety diagnosis

Heat maps of vehicle-vehicle conflicts are shown in Figure 3. The merging and rear-end conflicts between the On-ramp and the Burrard St. SB traffic flows have the highest frequency of vehicle-vehicle conflicts per square meter. Other vehicle-vehicle conflict zones are the Pacific St. WB approach (rear-end and side-swipe conflicts), the beginning of the On-ramp (rear-end conflicts), and the end of the Off-ramp (rear-end conflicts), for a total of four conflict-prone regions.

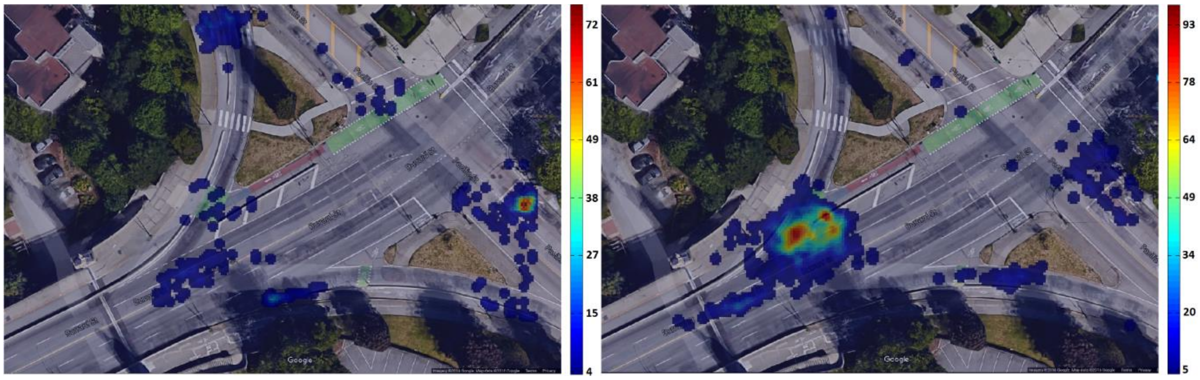

Figure 3: Vehicle-vehicle conflict frequency (conflicts/m^2) as indicated by PET (left) and TTC (right).

The distribution of vehicle-bicycle, bicycle-bicycle, and vehicle-pedestrian conflicts is shown in Figure 4. Conflicts involving bicycles and pedestrians are combined in the same heat maps because the number of conflicts involving pedestrians is small compared to the number of conflicts involving bicycles: 853 total bicycle-related conflicts were detected (507 vehicle-bicycle and 346 bicycle-bicycle), versus just

21 pedestrian-related conflicts. There are four zones with high bicycle conflict frequency: the bicycle crossing through the Off-ramp (vehicle-bicycle and bicycle-bicycle conflicts), the bike lane crossing through the On-ramp (vehicle-bicycle conflicts), the Burrard St. SB approach (vehicle-bicycle and bicycle-bicycle conflicts), and the crossing through Pacific St. WB approach (vehicle-bicycle conflicts). There are also conflicts scattered along Pacific St., as result of bicycles mixed in the motor vehicle flow.

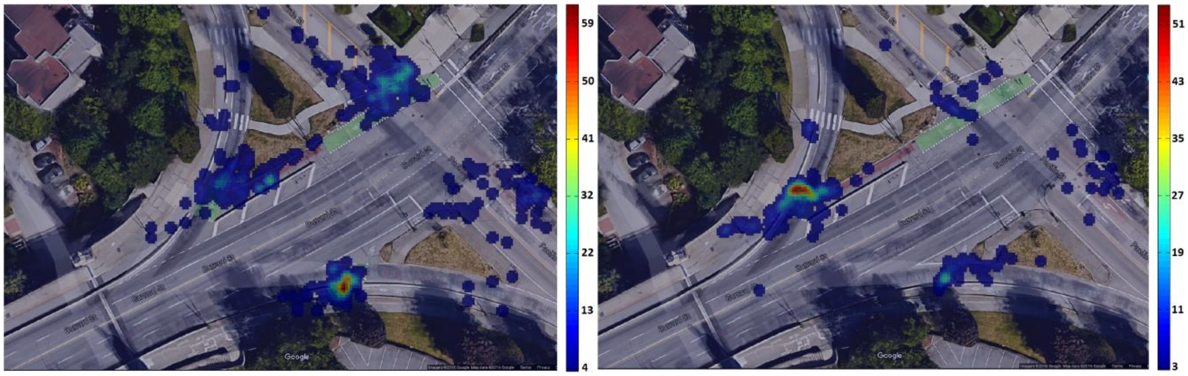

Figure 4: Vehicle-bicycle, bicycle-bicycle, and vehicle-pedestrian conflict frequency (conflicts/m^2) as indicated by PET (left) and TTC (right).

Table 2 shows the number of conflicts based on various indicator types/severities for each of the four bicycle-conflict-prone regions. Detected TTC and PET conflicts over 4 seconds are discarded due to low severity [41]. The highest observed PET-based conflict frequency per exposure is at the Off-ramp bicycle crossing, while a high frequency is also observed at the On-ramp bicycle crossing. The highest observed TTC-based conflict frequency per exposure is at the On-ramp bicycle crossing, which may be related to the complexity of the On-ramp design where, within a 50-meter segment, driver attention is divided among two crosswalks, a bicycle crossing, and a merging maneuver into the Burrard St. SB traffic flow. Moreover, a tree in the West traffic island partially obstructs the driver's view of bicycles in the approaching bike lane.

Table 2: Vehicle-bicycle and bicycle-bicycle conflicts per 1,000 road users.

	On-ramp bicycle crossing		Off-ramp bicycle crossing		Pacific St. WB approach		Burrard St. SB bike lane	
	TTC	PET	TTC	PET	TTC	PET	TTC	PET
0-1 s	7	7	2	5	5	14	0	13
1-2 s	20	28	3	25	2	18	1	14
2-3 s	33	17	5	35	2	5	0	4
3-4 s	16	4	11	4	1	2	0	1
Total	75	57	21	68	10	40	2	32

Figure 5 shows the temporal distribution of detected bicycle-related conflicts, combining PET- and TTC-based detected conflicts. Most conflicts involving bicycles occurred during the afternoon peak hours. Scene D, which covers the On-ramp bicycle crossing, shows the most detected conflicts.

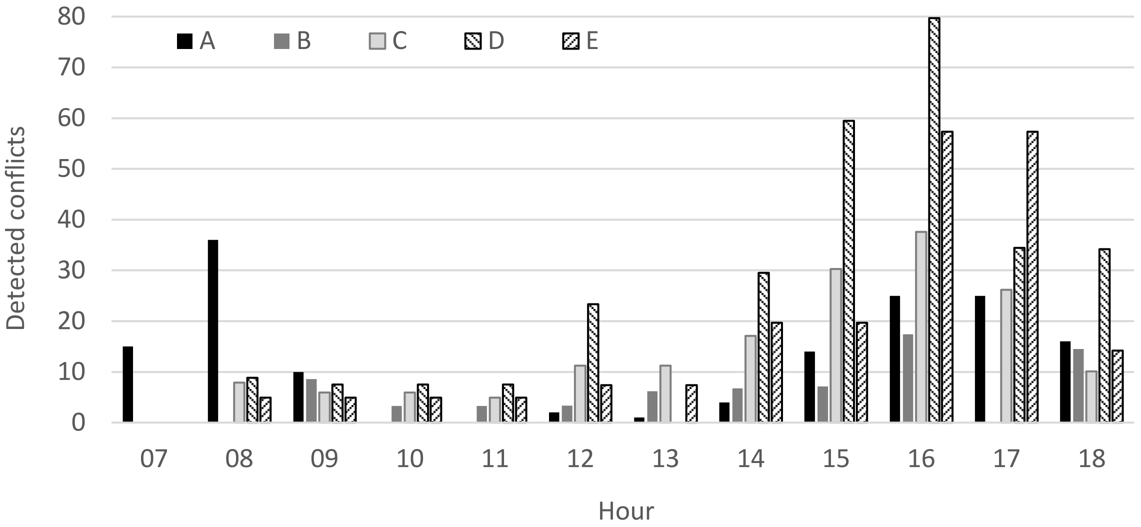

Figure 5: Vehicle-bicycle and bicycle-bicycle conflicts per scene throughout the day.

Table 3 summarizes the observed motor vehicle violations, ranked by violation rate (normalized to relevant traffic volume). Violations of failing to yield to cyclists and pedestrians in the On-ramp had 3 of the 4 highest counts and frequency rates, consistent with a high number of traffic conflicts in the On-ramp in Figure 4. Other violations also present the potential for severe collisions with a bicycle or pedestrian, including motor vehicles driving along bike lanes and crosswalks, or crossing during a red light (particularly on Pacific St.). Red-light and stop-bar violations on Pacific St. are associated with the conflict-prone zones in the Pacific St. WB approach and Burrard St. SB bike lane in Figure 4.

Table 3: Observed motor vehicle traffic violations.

	Type of violation	Location/ approach	Count of violations	Vehicle volume	Inappropriate negotiation rate (per 1,000 vehicles)
1	Stopping over the bike lane or not yielding	On-ramp	495	6,136	80.67
2	Arriving on a red light	Pacific EB	245	4,348	56.35
3	Stopping over the South crosswalk or not yielding	On-ramp	242	4,736	51.10
4	Stopping over the North crosswalk or not yielding	On-ramp	178	5,972	29.81
5	Changing lanes over solid lines into Pacific St.	Off-ramp	163	7,112	22.92
6	Crossing the stop line on a red light	Pacific WB	171	7,532	22.70
7	Changing lanes over solid lines or using the wrong lane	Pacific WB	165	7,532	21.91
8	Driving on the bike lane	On-ramp	8	900	8.89
9	Stopping over the bike lane or not yielding	Off-ramp	56	7,632	7.34
10	Driving on the bike lane	Off-ramp	2	444	4.50
11	Performing illegal turns into Pacific St.	Pacific WB	16	4,348	3.68
12	Changing lanes over solid lines into the Off-ramp	Pacific EB	7	2,900	2.41

Table 4 summarizes the observed bicycle and pedestrian violations, ranked by violation rate (normalized to relevant number of road users). Out-of-bounds violations by cyclists and pedestrians were relatively common, due to the pedestrian crossing restriction and lack of a marked bicycle crossing through the WB approach. Common violations also related to cyclist use of sidewalks, perhaps due to cyclist discomfort on less-separated facilities. Some cyclists descending the hill in the Burrard St. SB bike lane exceeded the 50 km/hr speed limit in the crossing. Unlike for motor vehicles, temporal (signal) violations were relatively uncommon for cyclists and pedestrians.

Table 4: Observed bicycle and pedestrian violations.

	Type of violation	**Location/ approach**	**Count of violations**	**User volume**	**Inappropriate negotiation rate (per 1,000 users)**
1	Pedestrian crossing through the ramp	Off-ramp	51	444	114.86
2	Cyclist not dismounting for the South crosswalk	On-ramp	26	248	104.84
3	Bicycle crossing out of bounds through the approach	Pacific WB	33	336	98.21
4	Bicycle crossing outside the bike lane or bicycle crossing	Off-ramp	39	444	87.84
5	Bicycle speeding in the bike lane	Pacific EB	31	988	31.38
6	Pedestrian crossing on ‘do not walk’ phase	Pacific EB	22	1,980	11.11
7	Cyclist not dismounting for the crosswalk	Pacific EB	21	1,980	10.61
8	Bicycle crossing on a red light	Pacific EB	7	1,032	6.78
9	Cyclist not dismounting for the North crosswalk	On-ramp	10	1,548	6.46

4.2 Analysis of proposed safety improvements

The results of the safety diagnosis were compared to a new design of the intersection, to evaluate how the changes will affect the identified safety issues. Figure 6 shows the new intersection design, with proposed improvements for vehicle, bicycle, and pedestrian facilities [42]. The most significant changes to the intersection are the replacement of the ramps with right-turn exclusive lanes in the EB and NB approaches. The redesign increases separation of motor vehicles, cyclists, and pedestrians in the intersection. The Burrard St. NB approach from the bridge will consist of four lanes: two for through-movements and two right-turn only. Pedestrian and bicycle crossings of this approach will still not be allowed. The redesigned Pacific St. WB approach will have marked bicycle and pedestrian crossings.

Four zones were identified in the safety diagnosis as having high vehicle-vehicle conflict frequency: the merger between the On-ramp and the Burrard St. SB traffic flows, the Pacific St. WB approach, the beginning of the On-ramp, and the end of the Off-ramp. Four zones were also identified in the safety diagnosis as having high frequency of conflicts involving cyclists and pedestrians: the bicycle crossings through the On- and Off-ramps and the crossings through both Pacific St. WB and EB approaches. The new design is expected to address many of the identified safety issues, but some are not addressed or are likely to migrate to different locations. In addition, the redesign may generate new issues. Table 5 and Table 6 summarize the safety issues found in the diagnosis, and qualitatively characterise the expected changes in safety with the new design.

Figure 6: Current (left) and proposed (right) designs for the Burrard St. and Pacific St. intersection. Source: City of Vancouver [42].

Table 5: Expected status of vehicle-related safety issues under the new design.

	Safety issue	**Location/ Approach**	**Addressed (*)**	**Potential migration**	**New issue**
1	Merging conflicts	On-ramp	●		
2	Rear-end conflicts	On-ramp	●	X	
3	Stopping over the bike lane or not yielding	On-ramp	●	X	
4	Stopping over the South crosswalk or not yielding	On-ramp	●		
5	Stopping over the North crosswalk or not yielding	On-ramp	●		
6	Motor vehicle driving on the bike lane	On-ramp	●		
7	Rear-end conflicts	Off-ramp	●		
8	Stopping over the bike lane or not yielding	Off-ramp	●		
9	Changing lanes over solid traffic lines into Pacific St.	Off-ramp	●		
10	Changing lanes over solid lines into the Off-ramp	Pacific EB	●		
11	Rear-end and side-swipe conflicts	Pacific WB	◖		
12	Crossing the stop line on a red light	Pacific WB	◖		
13	Motorcycle crossing on the bike lane	Off-ramp	○		
14	Vehicles arriving at the other side of the intersection on a red light	Pacific EB	○		
15	Changing lanes over solid lines or using the wrong lane for their movements	Pacific WB	○		
16	Performing illegal turns into Pacific St.	Pacific WB	○		
17	Changing lanes over solid lines or using the wrong lane for their movements	Pacific EB			X
18	Changing lanes over solid lines or using the wrong lane for their movements	Burrard NB			X

(*)● : Fully addressed - ◖: Partly addressed - ○ : Not addressed.

Expected changes in vehicle-related safety issues are summarized in Table 5. Both ramps are eliminated in the new design, so most conflicts and violations in these locations are expected to be addressed, with some potential for migration within the intersection. In the WB approach, vehicle lane-switching violations and side-swipe conflicts will be reduced by the introduction of a new traffic island on the Pacific St. EB approach, but rear-end conflicts caused by right-turn interruptions in the traffic flow of Pacific St. WB approach will remain. This latest conflict could be reduced by restricting the right-turn movement or by protecting the bicycle and pedestrian crossings with an additional signal phase. Some major violations such as motor vehicles entering the bike lane will be addressed, while illegal turns, stopping over crossings, and red-light running will not. In addition, the new right-turn movements at the Pacific St. EB and Burrard St. NB approaches are potential new safety issues (rear-end and side-swipe conflicts and lane-switching over solid line violations).

Table 6: Expected status of bicycle and pedestrian-related safety issues under the new design.

	Safety issue	**Location/ Approach**	**Addressed (*)**	**Potential migration**	**New issue**
1	Vehicle-bicycle conflicts	On-ramp	●		
2	Vehicle-bicycle conflicts	Off-ramp	●		
3	Bicycle crossing outside the bike lane or bike crossing	Off-ramp	●		
4	Pedestrians crossing through the ramp	Off-ramp	●		
5	Vehicle-bicycle conflicts	Pacific WB	●		
6	Bicycle crossing out of bounds through the approach	Pacific WB	●		
7	Cyclist not dismounting for the North crosswalk	On-ramp	◖	X	
8	Cyclist not dismounting for the South crosswalk	On-ramp	◖	X	
9	Cyclist not dismounting for the crosswalk	Pacific EB	○		
10	Pedestrian crossing on ‘do not walk’ phase	Pacific EB	○		
11	Bicycle crossing on red light	Pacific EB	○		
12	Bicycle speeding in the bike lane	Pacific EB	○		
13	Bicycle-bicycle and vehicle-bicycle conflicts	Pacific EB	○		
14	Vehicle-bicycle and vehicle-pedestrian right-turn conflicts	Burrard NB			X

(*)● : Fully addressed - ◖: Partly addressed - ○ : Not addressed.

Expected changes in bicycle and pedestrian-related safety issues are summarized in Table 6. The conflicts and violations in the ramps are expected to be addressed, with some potential for migration within the intersection. The introduction of protected bike lanes on Pacific St. will help to reduce vehicle-bicycle conflicts in Pacific St., and more separated bicycle facilities could reduce violations associated with cyclist use of sidewalks. Safety issues will remain in the Pacific St. EB approach bicycle and pedestrian crossings, with the possibility of increased conflicts as vehicles migrate from the On-ramp to the new right-turn lanes. There could also be new issues with cyclists accessing the EB protected bicycle lane on Pacific St. east of the intersection, without a protected bike lane in the NB approach.

5 Conclusions

This study demonstrates the application of automated computer vision systems to assess bicycle safety at a complex urban intersection. Major causes of vehicle-bicycle conflicts include failure to yield to bicycles at bicycle crossings in the Burrard Bridge on- and off-ramps, and vehicle red-light and stop-bar violations on Pacific St. Proposed improvements to the intersection design are expected to address many of the identified safety issues, while others will remain or shift to a new area of the intersection. Replacing the Burrard Bridge ramps with right-turn lanes in the intersection is expected to greatly reduce bicycle and pedestrian conflicts at this location. An *after* analysis will be completed in 2018, after implementation of the proposed improvements, to provide an ex-post comparison for the predictive assessment presented here.

Camera height, angle, resolution, and location were constrained by the City of Vancouver, and proved to be major limitations for the video analysis. In particular, some potential conflict regions could not be studied using the available video footage. Future work should increase video data extent, and video image quality must be prioritized for automated conflict analysis of cyclists and pedestrians. In addition, further research in computer vision is needed to develop more efficient and reliable software and increase sample sizes; the current method relies on manual video observations to filter false positive conflict detections. The capacity to detect and track stopped road users also needs improvement, as it is limited under current tracking algorithms and can cause missed-detections in conflicts involving stopped road users. More generally, the quantitative relationship among collisions, traffic conflicts, and traffic violations requires further research, particularly for interactions between motorized and cyclists.

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