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A Conflict-Based Safety Diagnosis of SCI Roundabouts Using a Surrogate Safety Measure Model

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Abstract: Recently, the surrogate safety assessment model has been considered for the safety performance analysis of roundabouts. This model can perform a detailed analysis of conflicts based on the trajectory data of vehicles inside the roundabout. The Separated Central Island (SCI) roundabout, as one of the roundabouts with distinct geometrical characteristics, holds the potential for safety evaluation using the conflict-based method. Therefore, in this study, a safety diagnosis of an SCI roundabout was conducted for the first time. In this study, a safety diagnosis procedure for SCI roundabout was first defined; for this purpose, vehicle trajectory data were obtained using an Unnamed Aerial Vehicle (UAV) and then entered into Surrogate Safety Measure Model software (SSAM 3.0). A case study was conducted on the only SCI roundabout in Iran, located in Mashhad. The parameters of Time-to-Collision (TTC), maximum speed difference of two vehicles involved in a collision (MaxΔV), and maximum speed of vehicles in collision (MaxS) were utilized to determine the type and severity of conflicts and risk analysis. The results of roundabout risk analysis showed that the severity level of conflicts is mainly of the injury type and that the lowest severity of conflicts is related to fatality. In addition, the highest frequency of injury conflicts is associated with lane-change conflict and the lowest frequency is linked to rear-end conflict. The highest and lowest frequency of damage conflicts are related to crossing and lane-change conflicts, respectively. After overall risk scoring, the severity level of conflicts is mainly related to injury type and the lowest severity of conflicts is associated with fatality; 31% of the total conflicts obtained are of the damaging type, and 69% are of the injury type. Finally, comparing the results of the conflict data with the 8-year crash data in such roundabouts confirms that in the absence of crash data in such roundabouts traffic engineers can use the roundabout analysis based on this study to predict the safety situation of such roundabouts before implementing engineering processes.

Keywords: risk assessment; surrogate safety; conflict-base; SCI roundabout

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1. Introduction

Due to many collision points, urban intersections are among the most critical places for accidents. Safety at intersections can be improved through the design of roundabouts [1,2]. A comparison between traditional intersections and roundabouts reveals that the severity of crashes in roundabouts is lower [3]. Data obtained from traffic crash reports represent a crash-based approach to safety assessment. However, in low- and middle-income countries in particular, crash data encounters problems around the accessibility, accuracy, and adequacy of data. Therefore, assessment methods that consider the parameters of conflicts (conflict-based approach) can be considered a suitable and reliable alternative for assessing the safety of roundabouts [4]. Surrogate Safety Measures (SSMs) are one of the most accurate approaches for functional analysis of roundabouts [5,6]. Currently, this method is used to assess developed roundabouts such as one-lane, two-lane, and Dumb-Bell Roundabouts, as well as recent alternative types of roundabouts such as Turbo roundabouts, traffic calming circles, etc., and alternative types of roundabouts at development phases, such as flower roundabouts, target roundabouts, etc. [7].

Transit Priority Systems (TSP) such as Bus Rapid Transit (BRT) types in urban at-grade intersections have always been a challenge for traffic and transportation engineers due to the resulting confrontation with other vehicles [8]. This challenge is defined at signalized intersections and roundabouts. In signalized intersections, engineers have implemented TSP accurately by changing and optimizing the timing of traffic lights. In roundabouts, however, a kind of developed roundabout with a Transitional Central Island, known as "Hamburger Roundabouts", are used [7]. This type of roundabout has been designed for the TSP, and can improve both traffic parameters and the safety of the public transit system due to the resulting reduction of conflicts with other vehicles [9–11]. Because Hamburger Roundabouts have separate lanes on the central island, they separate the movement of public transport vehicles from other vehicles (Figure 1a). In this research, this type of roundabout is called Separated Central Island (SCI). This name is due to the lack of a physical separation barrier in the central island for BRT buses (Figure 1b).

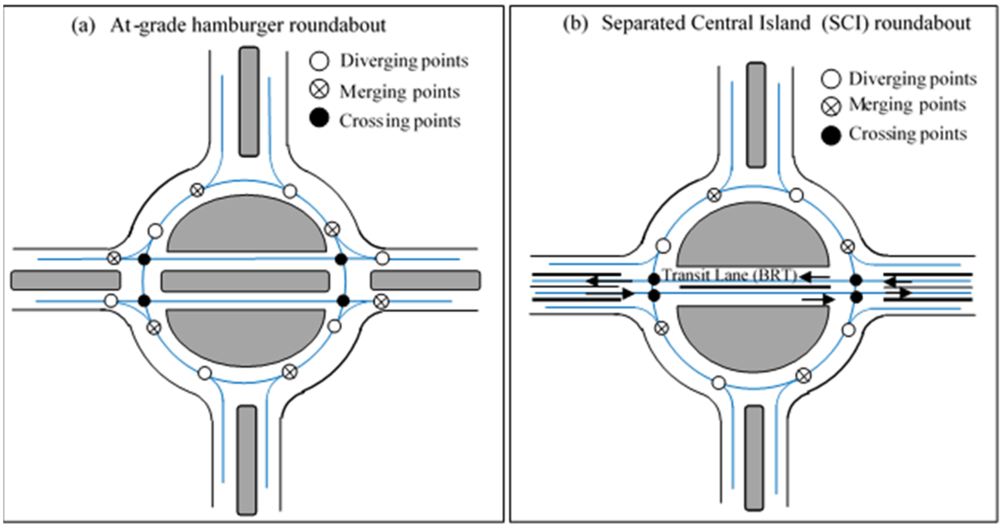

Figure 1. Conflict points of hamburger and SCI roundabouts.

Studies have provided a simple analysis of conflicts and possible collision points in Hamburger Roundabouts [7,12]. However, SCI roundabouts can have various conflict points (Figure 1b). Moreover, considering the driving behavior of vehicles, the number of crossing lanes, and the volume of traffic flow in these roundabouts, simple analyses such as Figure 1 (merging, diverging, crossing, and weaving points) cannot provide an accurate assessment of the number, type, and severity of roundabout conflicts.

The main objective of this study is to conduct an assessment analysis of the safety performance of SCI roundabouts. As a case study, conflicts in an SCI roundabout were calculated using the Surrogate Safety Assessment Model (SSAM). For this purpose, trajectory data of vehicles in the roundabout were collected using video recording by Unmanned Aerial Vehicle (UAV) and entered into Deep traffic video analysis software (DataFromSky). Then, the trajectory output of the vehicles was entered into SSAM 3.0 software for safety analysis. To achieve other research objectives, the output parameters of the SSAM were investigated. These other objectives included: (I) the number, type, and severity of conflicts based on the Time-to-Collision (TTC); (II) risk scoring of conflicts based on the speed difference of the vehicles involved in the collision (MaxΔV); (III) the maximum speed of vehicles against the TTC during a collision; and (IV) identification of zones prone to conflicts in SCI roundabouts as compared to conventional roundabouts. To accomplish the stated objectives, in the literature review section, the existing research gaps in studies conducted on SCI roundabouts are reviewed. Then, a novel diagnostic process devised specifically for SCI roundabouts is explained in the methodology section. Next, in the analysis section, risk analysis and scoring are carried out using two distinct methods, a new zoning system is established for diagnosing these roundabouts, and the obtained results are compared with the crash data collected from this roundabout. Finally, the important results of this research are presented in the conclusion section.

2. Literature Review

Studies regarding roundabout safety reveal that two main techniques, crash-based and conflict-based, have drawn the attention of researchers. The Traffic Conflict Technique (TCT) is proactive because there is no need to wait for collisions to be recorded before performing the analysis [13]. Table 1 shows the studies carried out in roundabout safety diagnosis using the conflict-based method. In most studies, the trajectories of vehicles inside the roundabouts have been obtained using the following two methods:

(i) Trajectories obtained from UAV footage and image processing
(ii) Trajectories obtained from simulation software such as VISSIM and AIMSUN

To employ the latter technique, in addition to various parameters such as vehicle speed, volume, and type of vehicle in the simulation software, the driving behavior of the vehicles at the entrance of and inside the roundabout (vehicle headways, longitudinal, lateral and acceleration maneuvers) should be calibrated to ensure that the results are reliable [14]. In taking videos with a UAV [15], the actual behavior is used after processing the image as a file in '.trj' format, which can be more suitable than the simulation technique. For this reason, the UAV method [16] was used in this study. In addition, according to Table 1, almost all studies of safety analysis applying the conflict-based method have utilized SSAM for performance analysis and roundabout safety diagnosis. To this end, SSAM 3.0 is used in this study. In SSAM, most studies have used the TTC and Post-Encroachment Time (PET). However, in addition to TTC and PET, other studies [17–21] have assessed the MaxΔV, MaxS, and Deceleration Rate (DR) as well. In this study, we used the TTC, MaxΔV, and MaxS indicators for risk analysis. The definitions of these parameters are as follows:

TTC: the minimum collision time between two vehicles that will collide with each other if they do not change their direction of movement [22].
MaxΔV: speed changes between two colliding vehicles [23].
MaxS: the maximum speed of each vehicle during the collision [23].

The risk analyses performed on the conflicts were done to determine the risk of conflict severity. These methods are usually based on the speed of conflict and the TTC [24–26]. In the current study, Hyden's method [24] was used to determine serious and non-serious conflicts. For the severity level, risk level, and Conflict Classification, the FHWA method was utilized [25].

Table 1. Studies conducted with SSAM related to roundabout safety.

Study (Year)	Roundabout Type	Trajectory Method Investigation	Performance Analysis	Indicators
Shawky et al., 2022 [4]	Conventional roundabout	UAV	SSAM	PET
Leonardi and Distefano 2023 [12]	Conventional roundabout and turbo-roundabout	Aimsun	SSAM	TTC, PET, DR, MaxS
Giuffrè et al., 2019 [17]	Single-roundabout Double-lane roundabout and turbo-roundabout	VISSIM and Aimsun	SSAM	TTC, PET, MaxS,

Table 1. *Cont.*

Study (Year)	Roundabout Type	Trajectory Method Investigation	Performance Analysis	Indicators
Bahmankhah et al., 2022 [18]	Conventional Roundabout	VISSIM	SSAM	TTC, PET, DR, MaxS, DeltaS
Karwand et al., 2023 [19]	Conventional Roundabout	VISSIM	SSAM	PET, TTC, Max DST, Max S
Vasconcelos, et al., 2014 [20]	Single-lane roundabout double-lane roundabout turbo- roundabout	Aimsun	SSAM	TTC, PET, DeltaS (Relative Speed)
Gallelli et al., 2021 [21]	Conventional roundabout and turbo- roundabout	VISSIM	SSAM	TTC, PET, DR, MaxS, DeltaS
Giuffrè et al., 2017 [27]	Double-lane roundabout Turbo-roundabout Flower roundabout Target roundabout	VISSIM	SSAM	TTC, PET
Tesoriere et al., 2021 [28]	Unconventional elliptical and turbo-roundabout	VISSIM	SSAM	TTC, PET
Giuffrè et al., 2018 [29]	Single-roundabout Double-lane roundabout and turbo-roundabout	VISSIM and Aimsun	SSAM	TTC, PET
Liu et al., 2020 [30]	Rotor design developed for a five-leg roundabout	VISSIM	SSAM	MaxΔV, TTC
Gallelli et al., 2019 [31]	Conventional Roundabout	VISSIM	SSAM	TTC
Virdi et al., 2019 [32]	Conventional Roundabout	VISSIM	SSAM	TTC
Ghanim et al., 2020 [33]	Signalized roundabout	VISSIM	SSAM	TTC, PET
Morando et al., 2018 [34]	Conventional Roundabout	VISSIM	SSAM	TTC, PET
Al-Ghandour et al., 2011 [35]	Single-lane roundabout	VISSIM	SSAM	TTC
Bulla-Cruz et al., 2020 [36]	Conventional Roundabout	VISSIM	SSAM	TTC, PET
Current study	Separated Central Island (SCI) roundabout	UAV	SSAM	TTC, MaxS, MaxΔV

In recent years, studies have been carried out on the safety of various roundabout alternatives, such as conventional roundabouts, single-, dual, and triple-lane roundabouts, elliptical roundabouts, flower roundabouts, turbo roundabouts, rotor roundabouts, and signalized roundabouts [6,8,37–41]. Regarding hamburger roundabouts or SCI, only traffic flow parameters have been evaluated, and only in two studies [9,42]. However, despite the use of such roundabouts in countries such as Spain and Sweden, few studies have addressed this issue. There is only one SCI roundabout in Iran, which was selected here as a case study. Therefore, the diagnosis of the safety of SCI roundabouts is the novelty of this article. According to the information presented in Table 1, all previous studies have examined the safety of roundabouts using simulation methods. Only two studies [4,13] have utilized UAVs for evaluation. However, these two studies solely used the SSAM method for diagnosis, and did not employ the risk scoring method for risk analysis. Among the studies listed in Table 1, only Liu et al. [30] employed the IOWA risk analysis. This analysis aims to develop an index to predict the Modification Conflict Factor (MCF). Other studies focused on developing an index to predict the number of conflicts in a method-oriented manner, while the present study deals with diagnosis, which is one of the main research fields in evaluating the safety of roundabouts [4,13]. To achieve this, a combined process has been defined, including diagnosis of SCI roundabouts to identify new areas prone to severe conflicts compared to conventional roundabouts, risk scoring for the entire roundabout, and a comparison of crash statistics.

3. Materials and Methods

A procedure was defined to diagnose the safety of SCI roundabouts. The videos prepared from the traffic flow, which included all types of motorized vehicles and pedestrians, were calibrated and analyzed using videography in the DataFromSky image processing software. The '.trj' file format was entered into SSAM 3.0 [43] as an output to calculate TTC, MaxΔV, and MaxS parameters. According to SSAM, types of conflicts were divided into three categories: crossing (conflict angle 0 to 30 degrees), rear-end (30 to 80 degrees), and lane-change (80 to 180 degrees) (Figure 2). Then, the risk analysis was applied using the Hyden [24] and FHWA [25] methods as the main criteria for the calculated parameters. Finally, the frequency of conflict severity, severity level, and class of each conflict were obtained (Figure 3).

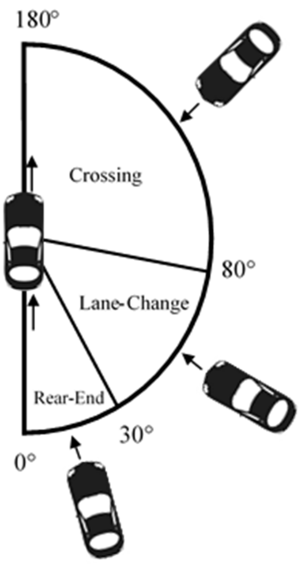

Figure 2. Conflict angle threshold [39].

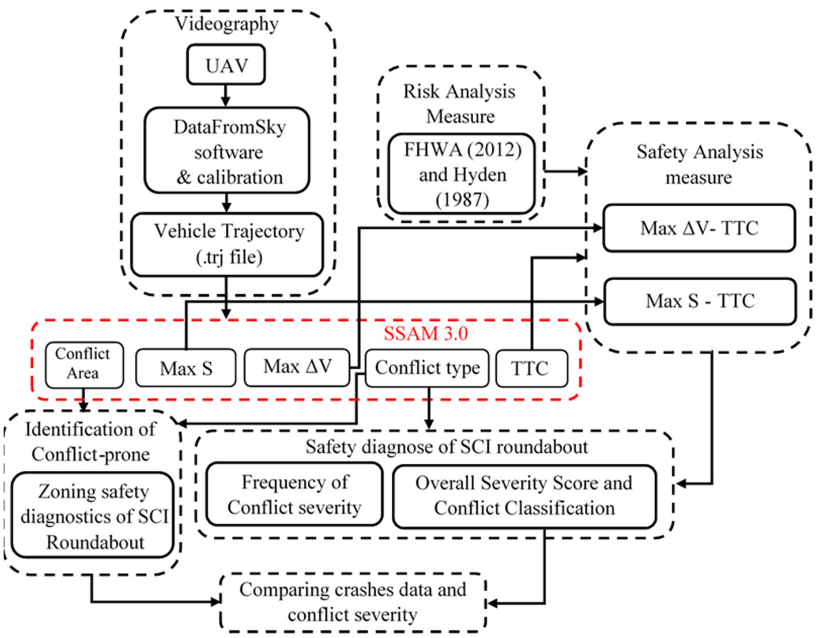

Figure 3. Defined safety diagnosis procedure [24,25].

3.1. Field Study of SCI Roundabout by UAV

As the only implemented SCI roundabout in Iran is the Barq Roundabout (Basij Roundabout) in Mashhad City, located at the intersection of Imam Reza and Bahar streets, it was chosen as a case study. Vehicle trajectories are required to calculate TTC, MaxΔV, and MaxS indicators in SSAM. To this end, filming was carried out using a Quantum 4-type unmanned aerial vehicle over the Barq roundabout during peak traffic hours. Then, the recorded videos were entered into DataFromSky. Figure 4a,b shows a sample of the images obtained of the roundabout and one of the conflicts in the roundabout, respectively. After entering the data, the film was first calibrated in DataFromSky. Parameters related to calibration included speed (approaches, circular movement in the roundabout, and vehicles stopped in the circular carriageway) and the locations of vehicles passing through the roundabout. To calibrate these, points prepared by GPS were used in the field observations. In the geo-registration section of the DataFromSky software (the location of the video by geographic coordinates, allowing measurement of speed and acceleration), the UTM points were entered and the calibration error value of the points was close to zero. After analyzing the videos, the trajectory output of the vehicles was prepared as a '.trj' file format.

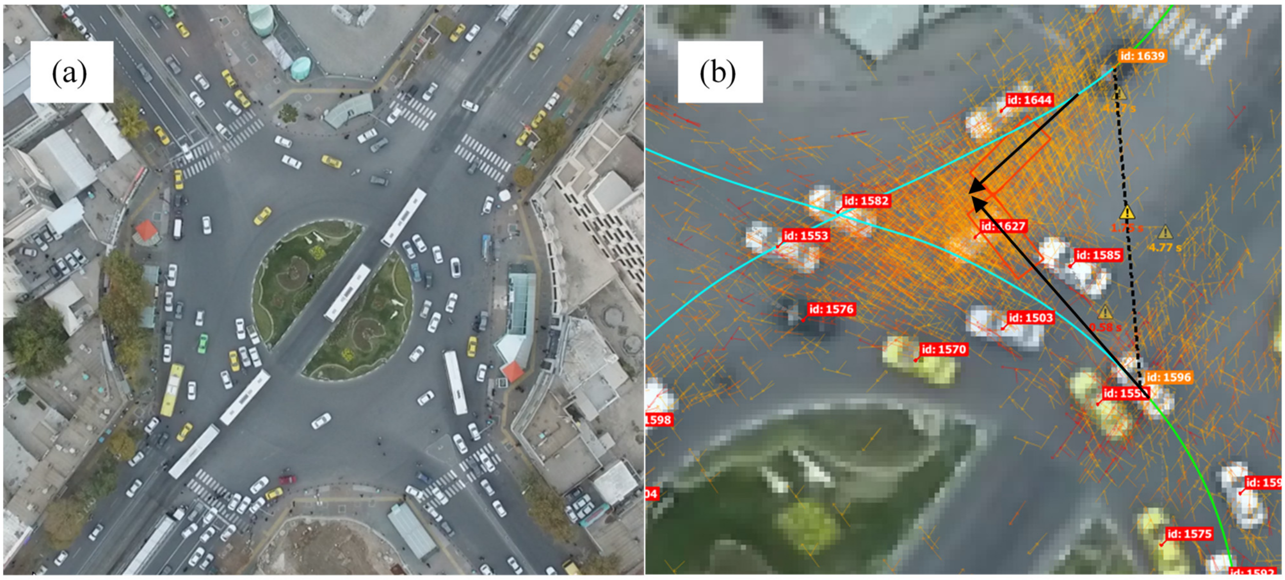

Figure 4. (**a**) An aerial image of a case study roundabout taken from the UAV and (**b**) an example of vehicle trajectories and TTCs.

3.2. Safety Analysis Measure

The '.trj' file format obtained from the analysis of the videos was entered into SSAM. To determine the risk severity levels based on Hayden's method, as updated in the FHWA study, the SSAM output parameters were obtained according to Figure 5 for the TTC and MaxS indicators. According to Figure 5, serious and non-serious conflicts were determined based on TTC and MaxS values for each conflict. The red line in Figure 5 shows the boundary between serious and non-serious conflicts.

To determine the risk scoring of the conflicts based on TTC and MaxΔV, the FHWA report of the University of Iowa [25] was used. This section divided TTCs into four categories, from low to extreme. In addition, the values obtained for MaxΔV were divided into three categories based on scoring from low to high. The overall scoring was obtained based on the sum of the scores for TTC and MaxΔV (from 1 to 6), which presents the classification of conflicts in three classes. If the sum of the risk scores equals 1 or 2, the conflict is placed in the potential class. If it is 3 and 4, the conflict is placed in the slight class. If it is 5 and 6, the conflict is placed in the serious class. The classes indicate respective severity levels of damage only, injury, and fatality. The highest conflict risk score was 6, corresponding to the high injury or fatality classification, while the lowest score assigned to conflicts was 1, classified as low injury or damage only. Table 2 shows the scoring method for the mentioned parameters and the total frequency of conflicts in the studied roundabout. The highest frequency of conflicts is related to $0 \leq \text{TTC} \leq 1.5$, which is a score of 3, and the lowest frequency is related to $\text{TTC} \geq 4$, which is assigned a score of 0. In MaxΔV scoring, more than 99% of conflicts are at the low risk level. By adding up the scores, we calculated that the risk scores of 1 and 2 contain 31.05% of conflicts, conflicts with risk scores of 3 and 4 contain 68.94%, and 0.01% of conflicts involve risk scores of 5 and 6.

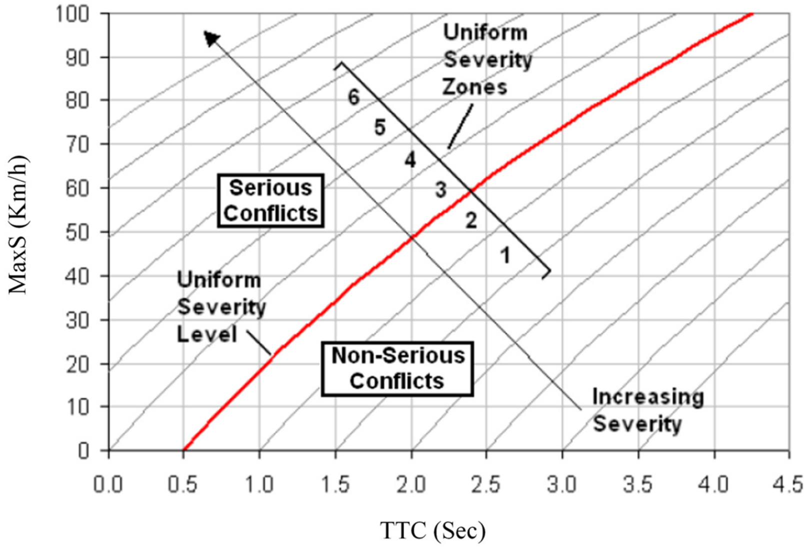

Figure 5. Uniform severity levels and severity zones developed by Hyden [24].

Table 2. Assigned TTC score based on [25].

TTC Score	TTC Range (s)	Frequency (%)	TTC Risk Level
3	$0 \leq \text{TTC} \leq 1.5$	51.6	Extreme
2	$1.5 \leq \text{TTC} \leq 2.5$	17.4	High
1	$2.5 \leq \text{TTC} \leq 4$	15.7	Moderate
0	$\text{TTC} \geq 4$	15.3	Low
MaxΔV Score	**MaxΔV Range (km/h)**	**Frequency (%)**	**Severity Level**
1	$\text{Max}\Delta\text{V} \leq 32$	99.98	Low
2	$32 \leq \text{Max}\Delta\text{V} \leq 64$	0.01	Moderate
3	$\text{Max}\Delta\text{V} > 64$	0.01	High
Conflict Classification	**Overall Severity Score**	**Frequency (%)**	**Severity Level**
Potential	1	15.35	Low ≈ Damage Only
	2	15.7	
Slight	3	17.4	Moderate ≈ Injury
	4	51.54	
Serious	5	0	High ≈ Fatality
	6	0.01	

4. Analysis

After analyzing the data using SSAM, a total of 10,653 conflict points were identified. Among these, 554 conflict points were related to crossing maneuvers, 7044 were caused by rear-end incidents, and 3055 conflict points were associated with lane change maneuvers. The highest percentage of conflicts observed was in rear-end conflicts, accounting for

66.12% of all identified conflicts. Lane change conflicts constituted 28.68% of the conflicts, while crossing conflicts represented 5.2% of the total.

In Figure 6a, the trajectory of vehicles within a specific interval of the analyzed video is illustrated to provide a visual representation of the vehicles' movements. Figure 6b depicts the distribution of conflict points scattered across the roundabout.

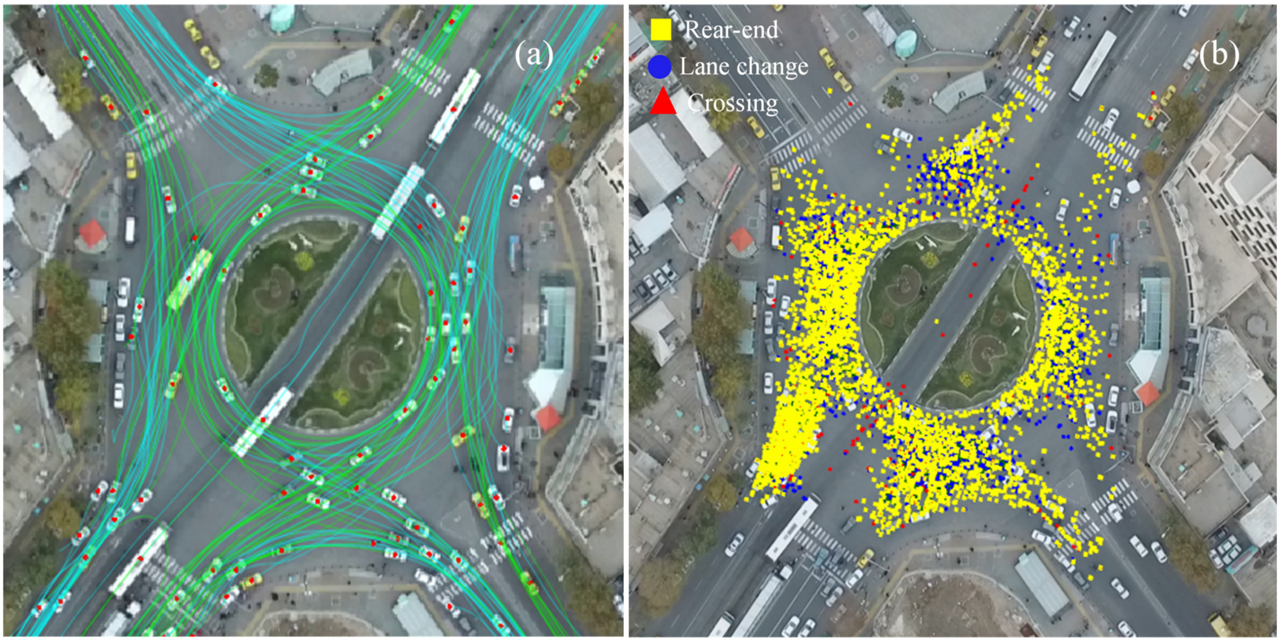

Figure 6. (**a**) Vehicle trajectories analysis and (**b**) total conflict points at the study location.

4.1. Crossing Conflicts

In Figure 7a, the data illustrate the frequency of crossing conflicts categorized by TTC. Figure 7b displays the distribution of crossing conflicts specifically within the roundabout. The majority of conflicts (55.23%) occur when the TTC falls between 0 and 1.5 s, indicating an extremely high risk level categorized as "Extreme". Conversely, the smallest proportion of conflicts (8.84%) happens when the TTC ranges from 1.5 to 2.5 s, which still represents a significant risk level. Additionally, 12.45% and 23.47% of conflicts are observed to have TTCs between 2.5 and 4 s (classified as "Moderate") and TTCs greater than 4 s (categorized as "Low"), respectively (refer to Table 3 for more details). More than 50% of crossing conflicts have the highest risk score for TTC.

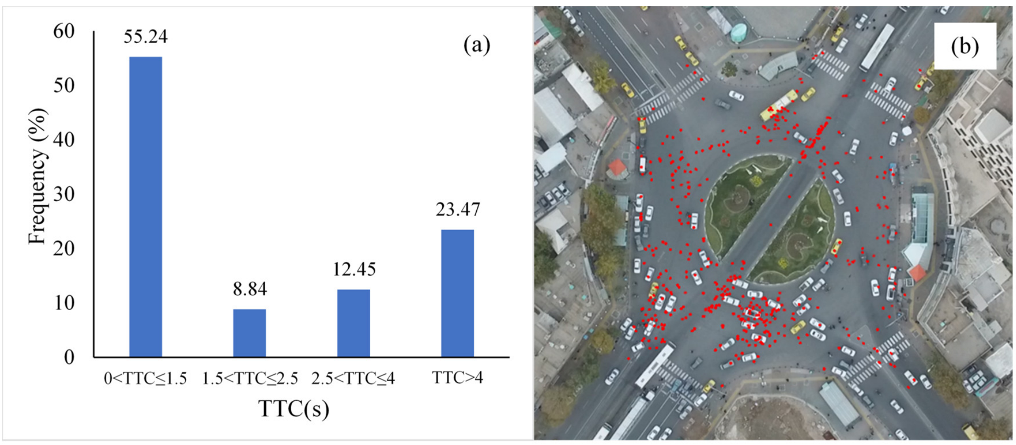

Figure 7. (**a**) Percentage of crossing conflicts versus TTC and (**b**) location of conflict points.

Table 3. Risk of crossing conflicts, showing score and frequency.

TTC ROC	ΔV ROC	Overall ROC	Frequency (%)
$0 \leq TTC \leq 1.5$	$Max\Delta V \leq 32$	4	305 (55.05%)
	$32 \leq Max\Delta V \leq 64$	5	0 (0%)
	$Max\Delta V > 64$	6	1 (0.19%)
$1.5 \leq TTC \leq 2.5$	$Max\Delta V \leq 32$	3	49 (8.84%)
	$32 \leq Max\Delta V \leq 64$	4	0 (0%)
	$Max\Delta V > 64$	5	0 (0%)
$2.5 \leq TTC \leq 4$	$Max\Delta V \leq 32$	2	68 (12.26%)
	$32 \leq Max\Delta V \leq 64$	3	1 (0.19%)
	$Max\Delta V > 64$	4	0 (0%)
$TTC \geq 4$	$Max\Delta V \leq 32$	1	130 (23.47%)
	$32 \leq Max\Delta V \leq 64$	2	0 (0%)
	$Max\Delta V > 64$	3	0 (0%)

Furthermore, when analyzing the risk scoring for MaxΔV, it is noted that 99.6% of crossing conflicts have MaxΔV values below 32 km/h, indicating the lowest severity level, which is labeled as "Low".

Following our comprehensive evaluation using the TTC and MaxΔV results, the ultimate risk scores for crossing conflicts are presented in Table 4. The most prevalent category is associated with the potential for causing injuries, accounting for 64.05% of the conflicts. Conversely, the least common category pertains to the risk of fatality, comprising only 0.19% of the total cases. For further details, please refer to Table 4.

Table 4. Classification of crossing conflicts: severity score and frequency.

Conflict Classification	Overall Severity Score	Frequency (%)	Severity Level
Potential	1	198 (35.76%)	Damage Only
	2		
Slight	3	355 (64.05%)	Injury
	4		
Serious	5	1 (0.19%)	Fatality
	6		

Hayden's method [24] was employed to assess the severity levels of crossing conflicts, allowing for the identification of potentially serious and non-serious conflicts. These estimates are depicted in Figure 8, where the MaxS values are plotted against the corresponding TTC values. The analysis reveals that 45.6% of crossing conflicts fall within the realm of serious conflicts.

Furthermore, as per information from [27], collision probabilities in newer roundabouts occur more frequently when TTCs are less than 1.5 s. This high-risk region is illustrated in red in Figure 8, representing the area with the greatest probability of an accident. Considering the presence of an excessive number of MaxS values and TTCs below 1.5 s, it is evident that 55.24% of crossing conflicts carry the potential for crashes.

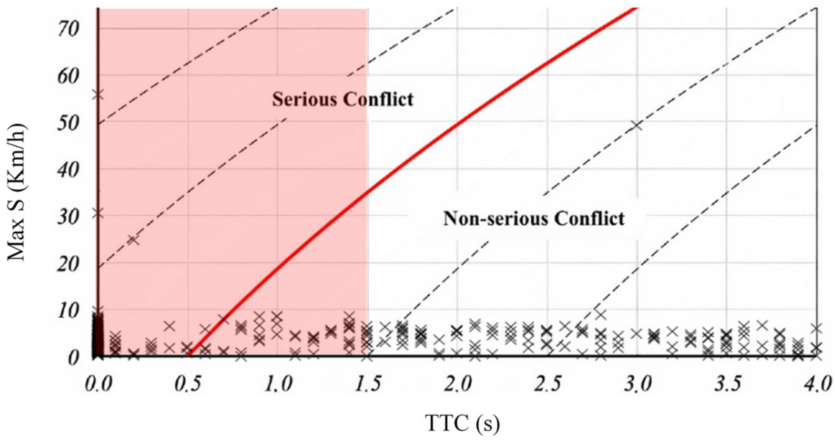

Figure 8. MaxS versus TTC for crossing conflicts.

4.2. Rear-End Conflicts

Figure 9a shows the frequency of rear-end conflict based on different TTC categories. Most conflicts related to TTC are between 0 and 1.5 (51.5%), which is the highest risk level (Extreme), while the lowest number of conflicts is related to TTCs greater than 4 s (High risk level) (15.6%). TTCs between 1.5 and 2.5 s account for 16.98% of conflicts (High) and TTCs between 2.5 and 4 s account for 15.91% (Moderate). Risk scoring based on MaxΔV indicates that all speed changes between vehicles are less than 32 km/h. Therefore, the lowest MaxΔV risk score (RS = 1) is assigned to rear-end conflicts (Table 5).

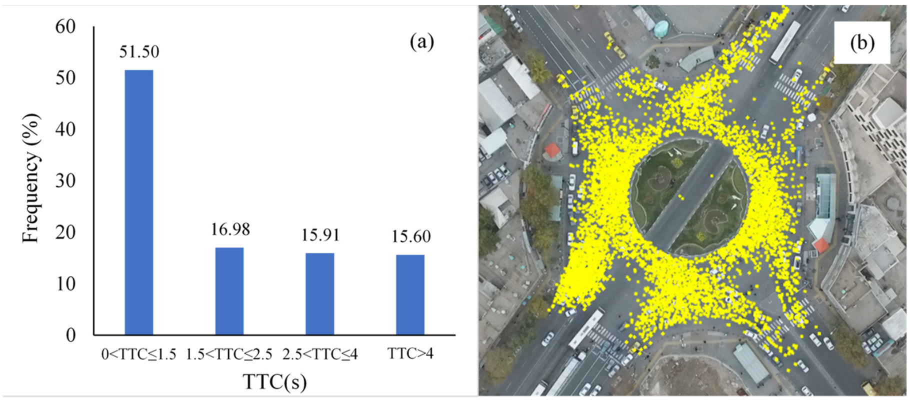

Figure 9. (**a**) Percentage of rear-end conflicts versus TTC and (**b**) location of conflict points.

Table 5. Risk of rear-end conflicts: score and frequency.

TTC ROC	ΔV ROC	Overall ROC	Frequency (%)
$0 \leq \text{TTC} \leq 1.5$	$\text{Max}\Delta V \leq 32$	4	3628 (51.5%)
	$32 \leq \text{Max}\Delta V \leq 64$	5	0
	$\text{Max}\Delta V > 64$	6	0
$1.5 \leq \text{TTC} \leq 2.5$	$\text{Max}\Delta V \leq 32$	3	1196 (16.98%)
	$32 \leq \text{Max}\Delta V \leq 64$	4	0
	$\text{Max}\Delta V > 64$	5	0
$2.5 \leq \text{TTC} \leq 4$	$\text{Max}\Delta V \leq 32$	2	1121 (15.92%)
	$32 \leq \text{Max}\Delta V \leq 64$	3	0
	$\text{Max}\Delta V > 64$	4	0
$\text{TTC} \geq 4$	$\text{Max}\Delta V \leq 32$	1	1099 (15.6%)
	$32 \leq \text{Max}\Delta V \leq 64$	2	0
	$\text{Max}\Delta V > 64$	3	0

The overall risk scoring results for this type of conflict in the studied roundabout are presented in Table 6. The findings indicate that the majority of conflicts are categorized as "Injury", accounting for 68.48% of the incidents. There are no conflicts resulting in fatalities, while conflicts causing only damage represent 31.52% of the total cases.

Table 6. Classification of rear-end conflicts: severity score and frequency.

Conflict Classification	Overall Severity Score	Frequency (%)	Severity Level
Potential	1	2220 (31.52%)	Damage Only
	2		
Slight	3	4824 (68.48%)	Injury
	4		
Serious	5	0	Fatality

Employing Hayden conflict severity levels, the TTCs obtained from the studied roundabout were plotted against the MaxS values of points with the potential for serious and non-serious conflicts (see Figure 10). According to the results, 31.9% of conflicts are placed in the area of serious conflicts. According to the study of Giuffrè [27], the safety assessment of conflicts with the highest crash probability for new roundabouts was performed based on TTCs of less than 1.5 s. According to the results, 51.5% of rear-end conflicts had a TTC of less than 1.5 s. This indicates that this type has the highest crash probability in SCI roundabouts.

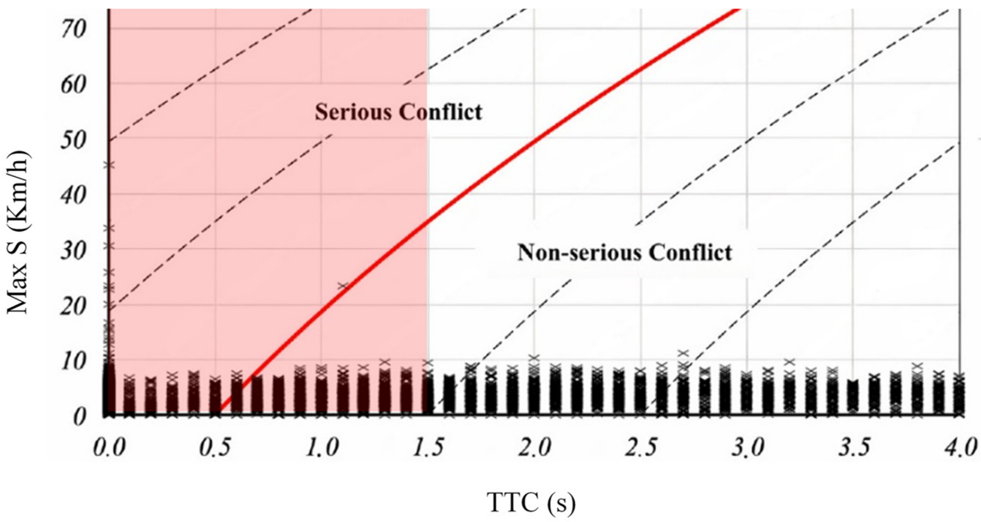

Figure 10. MaxS versus TTC for rear-end conflicts.

4.3. Lane-Change Conflicts

Regarding lane-change conflicts, the majority of conflicts related to TTC occur when the TTC is between 0 and 1.5 s, representing 51% of the total. This range corresponds to the highest risk level, classified as "Extreme". Conversely, the lowest number of conflicts are associated with TTCs greater than 4 s, accounting for 13.32% of the conflicts and falling under the "Low risk level" category. TTCs between 1.5 and 2.5 s account for 19.84% of the conflicts (categorized as "High risk"), while TTCs between 2.5 and 4 s account for 15.84% of the conflicts (classified as "Moderate risk") (refer to Figure 11a).

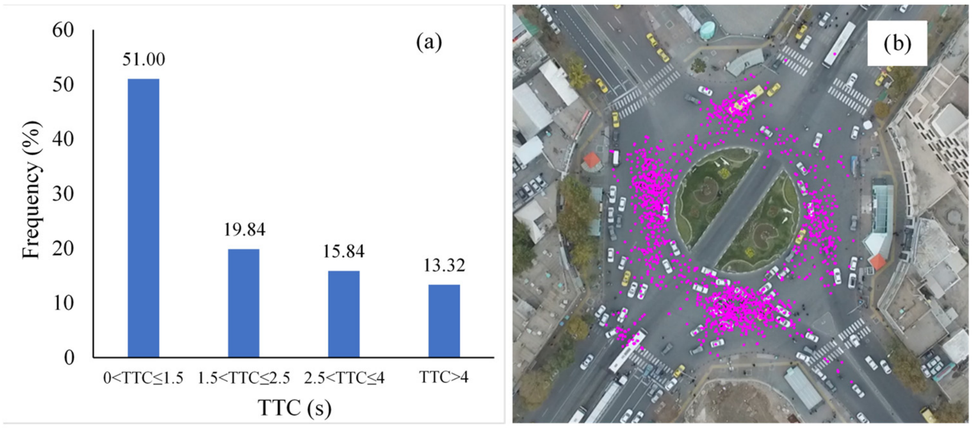

Figure 11. (**a**) Percentage of lane-change conflicts versus TTC and (**b**) location of conflict points.

Furthermore, evaluating the risk scoring based on the MaxΔV, it is observed that all speed changes between vehicles remained below 32 km/h. As a result, lane-change conflicts receive the lowest MaxΔV risk score (Table 7).

Table 7. Risk of lane-change conflicts: score and frequency.

TTC ROC	ΔV ROC	Overall ROC	Frequency (%)
$0 \leq TTC \leq 1.5$	$Max\Delta V \leq 32$	4	1558 (51%)
	$32 \leq Max\Delta V \leq 64$	5	0
	$Max\Delta V > 64$	6	0
$1.5 \leq TTC \leq 2.5$	$Max\Delta V \leq 32$	3	606 (19.84%)
	$32 \leq Max\Delta V \leq 64$	4	0
	$Max\Delta V > 64$	5	0
$2.5 \leq TTC \leq 4$	$Max\Delta V \leq 32$	2	484 (15.84%)
	$32 \leq Max\Delta V \leq 64$	3	0
	$Max\Delta V > 64$	4	0
$TTC \geq 4$	$Max\Delta V \leq 32$	1	407 (13.32%)
	$32 \leq Max\Delta V \leq 64$	2	0
	$Max\Delta V > 64$	3	0

The results of the overall risk scoring for such conflicts in the studied roundabout are shown in Table 8. The results show that most of the conflicts that occurred in these conflicts were injury-related (70.83%). There were no fatal conflicts, and damage only conflicts represented 29.17% of the total.

Table 8. Classification of lane-change conflicts: severity score and frequency.

Conflict Classification	Overall Severity Score	Frequency (%)	Severity Level
Potential	1	891 (29.17%)	Damage Only
	2		
Slight	3	2164 (70.83%)	Injury
	4		
Serious	5	0	Fatality

Based on Hayden's risk levels, 28.3% of lane-change conflicts fall into the category of serious conflicts (see Figure 12). Additionally, according to the red zone, 51% of the lane-change conflicts in the SCI roundabout have a TTC of less than 1.5 s, which falls within the range of conflicts with the highest probability of crashes.

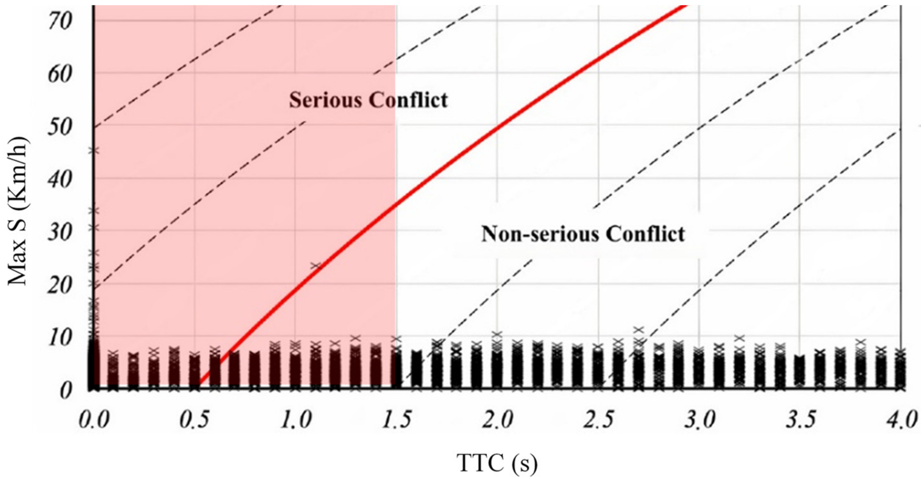

Figure 12. MaxS versus TTC for lane-change conflicts.

4.4. Zoning Safety Diagnostics of SCI Roundabout

In this section, safety zoning was conducted for the studied SCI roundabout as part of the roundabout diagnosis process. Taking into account the conflict angle of vehicles and the roundabout's geometric shape intended to prioritize the BRT (Bus Rapid Transit) public transit system, the roundabout was divided into 14 zones (as shown in Figure 13). Among these zones, four are related to the Weaving section (areas 3, 6, 9, and 12) of the SCI roundabout, two zones belong to the Crossing section (zones 13 and 14 in red color), four zones are associated with the Entry section (2, 5, 8, and 11), and four zones pertain to the Exit sections (1, 4, 7, and 10). Following the safety zoning of the roundabout, the number of each type of conflict was analyzed and examined based on the conflict angle for each of the 14 zones. Table 9 presents the results of the conflict analysis, displaying the number and percentage share of conflicts in all the defined zones on the SCI roundabout categorized by conflict angle.

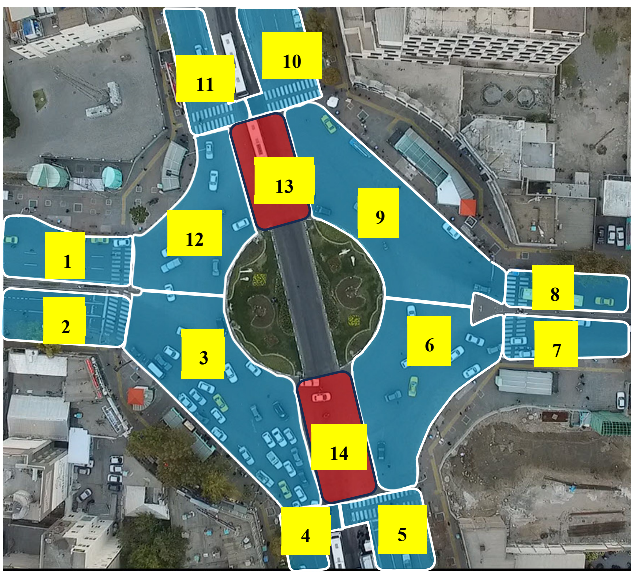

Figure 13. SCI roundabout zoning.

Table 9. Identification of conflict-prone zones based on the type of conflict.

Sections of SCI Roundabout	Safety Zone Number	Number of Conflict Type (%)		
		Crossing	Rear-End	Lane Change
Exit Section	1	18	72.13	9.87
	4	18.75	72.5	8.75
	7	21.95	41.46	36.59
	10	6.6	26.6	66.8
Entry Section	2	13.95	76.74	9.31
	5	7.69	87.69	4.62
	8	20.58	55.88	23.54
	11	3	93.93	3.07
Weaving Section	3	5.65	66.07	28.28
	6	4.93	46.71	48.36
	9	1	70.23	28.77
	12	3.82	49.36	46.82
Crossing Section	13	14.03	56.14	29.83
	14	13.42	68.45	18.13

Through the analysis of roundabout videos, it was observed that there are intersections between the BRT and cars at the borders of the 3rd to 14th zones as well as between the 9th and 13th zones. Additionally, all conflicts between BRT and cars that occur in the 14th and 13th zones are of the crossing type (as shown in Figure 14). Examination of the results revealed that 37% of the total crossing conflicts involve BRT and car interactions, signifying a significant proportion of the overall crossing conflicts. Consequently, employing this zoning method allowed us to identify two conflict-prone zones (zones 13 and 14) within these roundabouts, in contrast to conventional roundabouts.

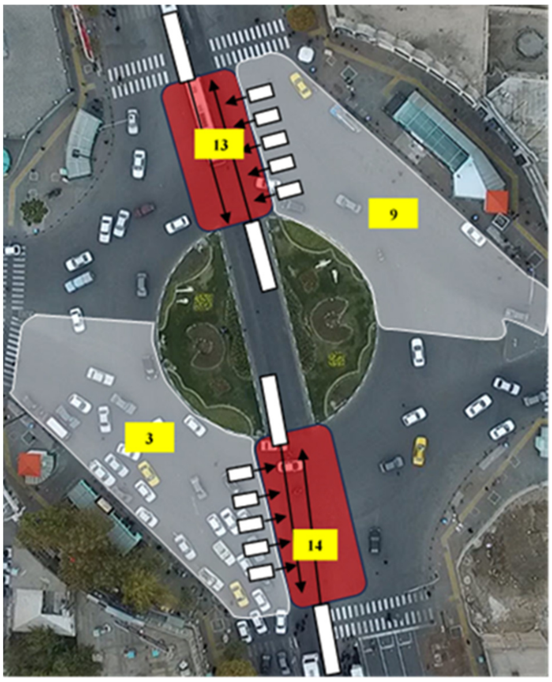

Figure 14. The area prone to conflict between BRT and car.

To achieve this, the zones were analyzed separately. To do this, the input volumes (circulating volumes in the roundabout) were calculated for zones 3 to 14 and 9 to 13 by setting up a counter gate in DataFromSky. The conversion rate of the number of passing volumes from the two traffic flows, cars and BRT (Bus Rapid Transit) into conflicts was assessed. For this evaluation, the trend of changes in the ratio of BRT to car volumes (V_{BRT}/V_{Car}) over 45 min intervals was analyzed in nine 5 min segments using aerial images captured by the UAV. The trend of changes reveals that the number of conflicts between BRT and cars rises as the ratio of BRT to car entry volume increases every five minutes (Figure 15). Therefore, it can be inferred that as the volume of vehicles in zones 13 and 14, increases along with the circulating vehicle volume in the roundabout, the incidence of crossing conflicts between buses and cars increases as well.

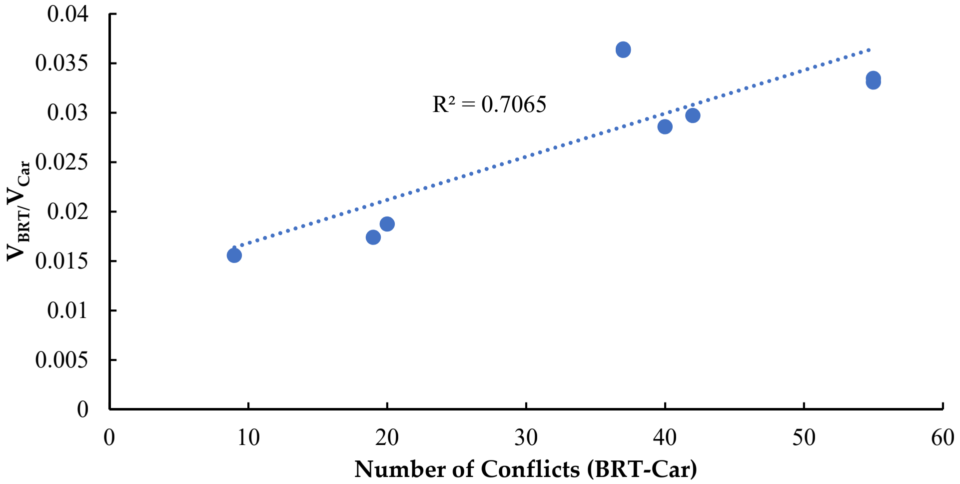

Figure 15. The relationship between the VBRT/VCar ratio and the number of conflicts.

4.5. Comparing Crash Data and Conflict Severity

Figure 16 shows the number of crashes in the studied roundabout in Mashhad. These statistics are from 2011 to 2018 and have been prepared by Mashhad Police Department. In the years that the study was conducted, there were no fatal crashes, 84% of the crashes were injuries, and 16% were damage-only crashes. In contrast, when investigating the safety of the studied roundabout through conflict-based risk scoring, the results showed that 69% of the conflicts were related to injury and 31% were damage-only. In this study, because we had limited access to the accident data recorded by the police for the years 2019 to 2022, we utilized 8-year data from 2011 to 2018.

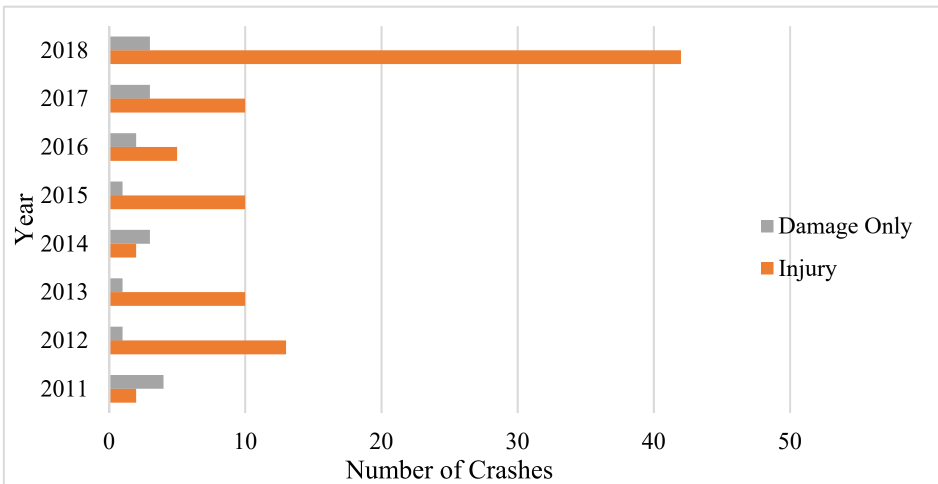

Figure 16. Number of crashes per year from 2011 to 2018.

According to Figure 16, only the statistics for two years, 2011 and 2014, indicate that the number of injury crashes was more than that of crashes causing damage only; in these years, there was only a slight difference (maximum of two crashes). For all the years, cumulatively or average, the total number of yearly injury accidents is more (indeed, more than double) the number of damage crashes for the studied roundabout. Figure 17 shows that among all the identified conflicts, only one was at the fatal severity level, which was not regarded due to its low frequency. The number of injury conflicts was two times that of damaging conflicts. A comparison of the results of conflict risk severity obtained from the study of the number of conflicts and crash data for the roundabout shows a significant relationship between the frequency of conflict severity and crashes in the roundabout.

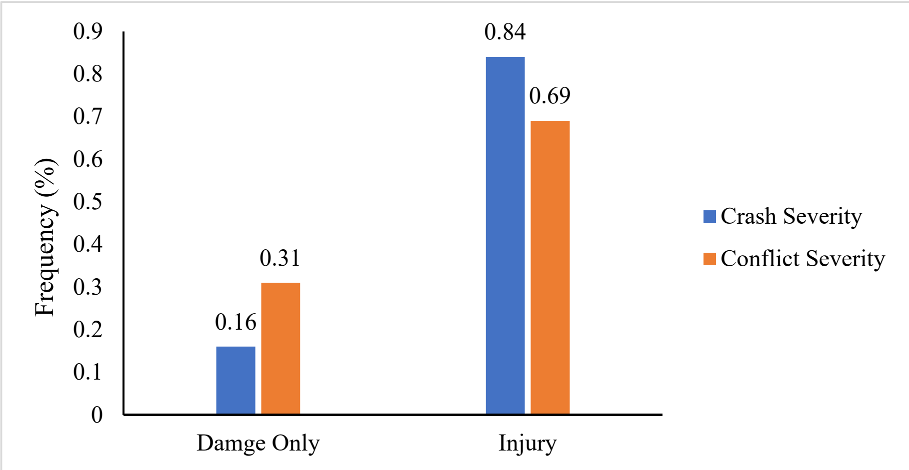

Figure 17. Comparison of crash and conflict severity.

5. Conclusions

This study was undertaken to analyze the safety performance of Separated Central Island (SCI) roundabouts in the context of a transit priority system. To achieve this goal, a case study was conducted on the sole SCI roundabout located in Mashhad, Iran. A safety diagnosis procedure was established utilizing trajectory data acquired from a UAV and analyzed using SSAM software. The results of the data analysis concerning the indicators of Time-to-Collision (TTC), maximum change in vehicle speed (MaxΔV), and maximum lateral acceleration (MaxS) for the vehicles involved in conflicts are as follows:

- It is concluded that TTCs between 0 and 1.5 s have the highest frequency compared to other categories. The lowest frequency of the TTC category is related to TTCs that are longer than 4 s. Therefore, more than 50% of conflict points have extreme risk levels.
- It was observed that more than 99% of the vehicles in the roundabout are moving with a speed difference of 32 km/h or less. In conclusion, the majority of vehicles in the roundabout are maintaining a safe speed difference. This is likely attributed to the implementation of traffic calming measures and high traffic flow density. The number of conflicts is primarily linked to the injury type, with the lowest number occurring in cases of fatality. Out of all conflicts, 31% are of the damaging type, while 69% are injury-related. When examining conflict types individually, lane-change conflicts have the highest frequency of injury, while rear-end conflicts have the lowest frequency. On the other hand, crossing conflicts have the highest frequency of damage, while lane-change conflicts have the lowest.
- The MaxS versus TTC diagram was used to categorize conflict points into serious and non-serious conflicts. Among the conflict types, 45.6% of crossing conflicts, 31.9% of rear-end conflicts, and 28.3% of lane-change conflicts fell into the category of serious conflicts. However, when assessing the risk levels in the roundabouts for collisions involving crossing (55.24%), rear-end (51.5%), and lane-change (51%) conflicts, it was

found that these types of conflicts have the highest probability of resulting in crashes in this type of roundabout.
- Our analysis of 8-year crash data and the severity of conflicts indicates that crashes and injuries make the most substantial contribution to accidents in these roundabouts. Fortunately, crashes and fatal conflicts represent the lowest quantities, and are negligible for conflicts. In the 8-year crash data this value is zero, which depicts the accuracy of the conflict-based safety assessment approach used in this study. Therefore, if there is a traffic flow in the form of prioritized public transit in similar roundabouts, the findings of this study can be applied. In other words, if traffic and urban safety designers and engineers prioritize TSP and manage to convert conventional roundabouts into SCI roundabouts, the findings of this study can offer valuable insights into both overall and specific implications. Additionally, this analysis can provide an initial forecast of the severity, types, and frequency of conflicts within different areas of SCI roundabouts.
- The use of surrogate safety assessment models has been successfully applied, and appears crucial for future studies on rural and urban roundabouts due to limited and/or inaccurate crash data. For future studies on SCI roundabouts, we propose investigating the influence of the length of the separated area in the central island and the impact of traffic lights on these roundabouts to prioritize the public transit system and improve the safety performance of SCI roundabouts.

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