Analysis of Drivers' Behaviour at Different Road Safety Treatments in the City of Ottawa

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Abstract

Investigation of the effectiveness of different road safety treatments is essential to maximize the returns on road safety initiatives and expenditures. An investigation based on collision data alone would not provide the complete picture of the effectiveness of such treatments as collisions are known to be random and rare events. Therefore, such an investigation should also involve an evaluation of drivers' behaviour at the different treatments. This paper presents a comprehensive analysis of drivers' behaviour at road safety treatments that target improving safety at intersections and midblock or road segments. Namely, the paper examines roundabouts and red-light cameras (RLCs) as intersection safety treatments and Dynamic Speed Display Signs (DSDSs), speed cameras, and road centerline signs as segment safety treatments. Drivers' behaviour at each treatment type was examined using video data collected in the City of Ottawa. The video data collection covered 15 intersections, including 5 roundabouts and 10 signalized intersections (five with RLCs and five without RLCs) and 15 road segments including 5 segments for each treatment type, which are speed cameras, DSDS, and road centreline signs.

The safety impacts of segment treatments on driver behaviour were evaluated using a change of vehicle speed as a surrogate safety measure. On the other hand, the surrogate safety measures examined at intersection treatments were deceleration rate and Time-To-Collision (TTC) at RLCs and were Post-Encroachment Time (PET), TTC, and speed at roundabouts. The analysis indicated that RLC sites experienced more severe rear-end conflicts and harder deceleration compared to non-RLC signalized intersections. The PET and TTC analysis results for roundabouts showed a relationship between the ratio of number of conflicts to traffic exposure, termed as risk ratios, and collision frequency. The segment treatment analysis showed a change in speed from upstream to downstream speed cameras and DSDSs or before to after the installation of road centerline signs. A speed reduction of 12.18%, 9.39% and 8.9% in mean speed was observed at speed cameras, DSDSs and road centerline signs, respectively. The speed cameras also had a 40.40% compliance rate increase which is the highest increase within the segment treatments.

1 Introduction

Continuous population growth coupled with economic development has resulted in increasing demands for road transportation associated with traffic safety problems. In striving to improve traffic safety and reduce the social and economic impacts of traffic collisions, the Council of Ministers Responsible for Transportation and Highway Safety adopted in 2016 the Road Safety Strategy (RSS) 2025 to improve road safety in Canada (Transport Canada 2022). Several initiatives have been implemented within the City of Ottawa, and other Canadian cities, to adjust the behaviour of road users and mitigate risky behaviour. For example, the City of Ottawa currently lists 77 locations where red-light cameras (RLCs) have been installed to enforce traffic violations involving running the red light at signalized intersections. Ottawa also started to utilize automated speed cameras at school zones, where 17 sites are already listed as community safety zones with speed cameras (City of Ottawa n.d.). Ottawa has also installed by 2020 around 575 electronic speed boards that display the speed limit and approaching vehicle's speed. Additional safety treatments that have been implemented in Ottawa include converting intersections to roundabouts, where Ottawa lists 21 intersections with roundabouts as of November 2020 (City of Ottawa n.d.) and adding centerline road signs in the spring and summer seasons. Both of these latter programs use road features to adjust motorists' behaviour while the difference of cost of the two treatment types is quite obvious.

Several studies in the literature have examined the effects of different safety treatments on collision frequency and severity. Results are sometimes mixed and are often related to changes in driver behaviour. For example, a recent study in the City of Ottawa showed around 15% increase in the total number of collisions with roundabout installation in place of a stop-controlled intersection but more than 40% reduction in angle collisions and collisions involving injury or fatality (Abolhassani et al 2023). Similarly, RLCs in Ottawa were shown to reduce severe collisions involving injury or fatality while increasing property damage only (PDO) collisions (Saffarzadeh et al 2023). Therefore, a scientific study to assess the changes in motorists' behaviour at different safety treatments is essential to complement collision-based studies and confirm the change in driver behaviour at these treatments. This paper evaluates the specific impacts of the different road treatments on drivers' behaviour to examine if these treatments adjust the behaviour of motorists to avoid risky behaviour and adopt safer behaviour. In general, the five treatments examined in the study can be classified into two broad categories: intersection treatments, which include RLCs and roundabouts, and segment treatments, which include speed cameras, DSDSs, and road centerline signs. These treatments are commonly used in different municipalities, and the findings can be of interest to road authorities throughout Canada.

2 Methodology

As mentioned earlier, to assess the expected benefits of treatments as a traffic enforcement and safety improvement tool, this study presents a comprehensive traffic conflict analysis of video data at different safety treatments to examine the impacts of these treatments on driver behaviour. For each treatment, the most relevant traffic conflict indicators or surrogate safety measures were assessed. The indicators employed in the study of roundabout driver behaviour are Post-Encroachment Time (PET) and Time-to-Collision (TTC) at merging zones. For the assessment of RLCs, TTC and deceleration rate were used as traffic conflict indicators. Vehicle speed was the indicator analyzed for speed cameras and DSDSs to assess the drivers' behaviour upstream and at the treatment. For road centerline signs, speed was also used to assess behaviour before and after installation.

3 Site selection

For the RLC treatment, ten signalized intersections were selected for video data collection, split as five RLC intersections (treated sites) and five non-RLC intersections (untreated sites or reference group). All intersections are located in urban areas, and all of them are four-leg intersections. Furthermore, the untreated sites were selected from locations where there are no other RLC intersections within an 800-m buffer to avoid potential spillover effects (Contini and El-Basyouny 2016). In studying the roundabouts, five one-lane, four-legged roundabouts, which correspond to the configuration of most of the roundabouts in the City of Ottawa, were selected. During this study, Ottawa had eight-speed camera sites. For this study, five locations of speed cameras with an installation date of 2019 were selected. One location is a four-lane divided road while the other locations are two-lane undivided. For DSDSs, five sites in school zones were selected. This selection also allows for comparison against speed cameras, which are also installed in Ottawa in school zones. Five road centerline signs were selected to investigate the driver's behaviour at these treatments. All the road centreline signs are installed on two-lane undivided collector roads in school zones with speed limits of 40 km/h and 50 km/h. All segment treatments in school zones were considered for analysis because traffic safety near schools has always been a serious concern, and high populations of children can be found in areas surrounding schools. Figure 1 shows all selected sites for video data collection.

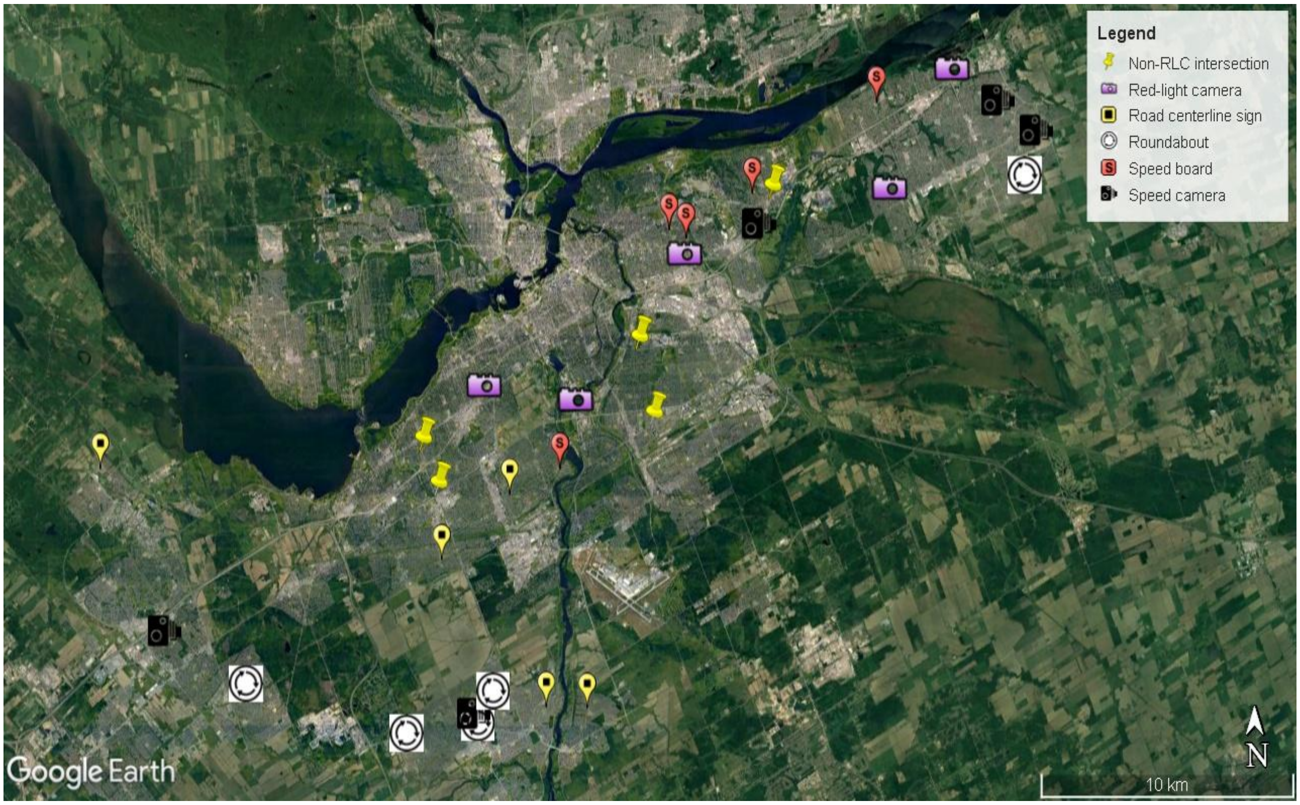

Figure 1: Locations of the selected sites for video data collection

4 Video Data Collection

The video data for all three types of segment treatments were requested from the City of Ottawa and were collected by the Miovision group. The video recording data for the segment treatments were collected using a 720p resolution camera with a horizontal field of view of 45 m (150 ft). Video data collection for the intersection treatments was performed by the research team with two GoPro Hero 8 cameras (1080p) for gathering the video data at each roundabout and only one camera at each RLC or non-RLC signalized intersection. The main goal of the video data collection was to cover all approaches to the roundabout, cover the RLC approach at the RLC intersection, or cover one approach at the non-RLC intersection.

5 Video Data Processing

The video recording data of intersections were analyzed through T-Analyst software. The software was developed by researchers at Lund University, Sweden, through the European Union's Horizon 2020 research and innovation program (Johnsson, et al. 2018). The videos of segment treatments were processed using Kinovea software, which is a free, open-source software that has been used in different applications including surrogate measures of road safety, e.g., (Mohanty, Panda and Dey 2021). Finally, the output data were processed using a MATLAB script to estimate the surrogate safety measures.

5.1 Speed Analysis

Speed analysis was performed for segment treatments to investigate the speed profiles upstream/before installation and downstream/after installation of the treatment. For speed cameras and

DSDSs, the upstream and downstream areas for each treatment were considered and defined by finding the location of the treatment in Google Maps. For the road centerline signs, the data were taken "before installation" and "after installation" as these treatments are removed in the snow seasons of the year to allow for the snow removal process. The speed profile for each vehicle was collected using video processing. Several data were extracted at different locations relative to the treatment including mean speed and 85th percentile speed.

5.2 PET Analysis

PET is the time taken from the first user passing a potential collision point to the arrival of the following road user. This measure is more suitable for assessing potential conflicts between intersecting trajectories. PET was examined at roundabout merging zones to identify the potential safety issues and risky behaviours associated with yielding behaviour at merging zones. Each roundabout was divided into four quarters. PET was calculated from the vehicles' trajectories extracted using the T-Analyst software. MATLAB script was developed to analyze the extracted vehicles' trajectories from T-Analyst Software and find PET for each interaction. A PET value of up to 2 s was considered a close interaction or a traffic conflict. Thus, the PET values and frequency of critical PET values (PET ≤ 2 s) were examined for each quarter and the whole roundabout during peak and off-peak periods to explore the variations in driver behaviour under different traffic volumes.

5.3 TTC Analysis

TTC denotes the time for two road users on a collision course to collide if their speeds and travelling paths remain unchanged. TTC has often been used as a measure for safety evaluation. Specifically, the larger the TTC value, the lower the risk of a collision, and vice versa. The lowest TTC value during an interaction of two vehicles (TTC_{min}) is the most common and most critical TTC indicator. TTC_{min} under 2 seconds was considered as a severe conflict. In this research, a MATLAB script was developed to analyze the extracted vehicles' trajectories from T-Analyst Software and find TTC_{min} for each interaction, which will simply be referred to as the TTC value for each interaction. Again, the TTC values and frequency of critical TTC values (TTC ≤ 2 s) were examined for each quarter and the whole roundabout during peak and off-peak periods to explore the variations in driver behaviour under different traffic volumes. For RLCs, a similar analysis was performed for the RLC approach at each treated intersection and one approach at each untreated intersection during peak and off-peak periods.

5.4 Deceleration Rate

Previous research has generally indicated that rear-end collisions increase at RLC intersections. The element that could play a role in explaining an increase in rear-end crashes is the hypothesis that some drivers may brake abruptly and unexpectedly when realizing the presence of RLC (Erke 2009). Even familiar drivers may decide to apply hard brakes to stop before the intersection and avoid travelling through the intersection in the yellow interval. Therefore, the deceleration rate is a traffic conflict indicator that can test this hypothesis by examining the differences in driver behaviour at RLC and non-RLC intersections. In this study, the decelerations of all vehicles approaching a sample of five RLC and five non-RLC (treated and untreated) intersections were collected in the yellow and red intervals. Because the trajectory of each vehicle had multiple measurements indicating their position, speed, and deceleration, the surrogate measures extracted for each vehicle were the maximum and mean deceleration. Finally, the average maximum deceleration for all vehicles and the average mean deceleration for all vehicles were calculated for each site in the peak and off-peak periods.

6 Intersection Treatment Results

6.1 Analysis of PET at Roundabouts

Table 1 summarizes the main statistics of the PET conflicts values observed at each roundabout. For all five roundabouts, for the PET conflicts (PET ≤ 2 s), the mean PET values were 1.38 s and 1.37 s during peak and off-peak periods, respectively. Using the independent samples *t*-test and non-parametric tests, the difference between mean PET values during peak and off-peak periods was statistically insignificant at all five roundabouts at a 5% level of significance. Furthermore, PET was categorized into two types, are the lead and lag PET. Lead PET is the time interval between the arrival of a circulating vehicle and the later arrival of an approach vehicle at an intersection point (the circulating vehicle arrives at the intersection point first). Lag PET is the time interval between the arrival of an approach merging vehicle and the later arrival of a circulating vehicle at an intersection point. In examining the difference between lead and lag PET conflicts, Figure 2 shows that lag PET conflicts generally have smaller PET values than lead PET conflicts. Testing the significance of this difference produced conflicting results and showed that the difference was statistically significant at a 5% level of significance for three roundabouts but insignificant for the other two. Finally, the linear correlation between the number of conflicts and traffic volumes was examined and revealed a relatively strong correlation between almost all conflict frequencies and traffic volumes. For example, total roundabout volume (sum of volume on all approaches) has correlation coefficients of 0.637, 0.588, and 0.668 with the total number of PET conflicts, number of lead PET conflicts, and number of lag PET conflicts, respectively.

Table 1: Summary of PET statistics of all conflicts (PET ≤ 2 s) on observed roundabouts.

Intersection	Off-Peak				Peak			
	Minimum	Number	Mean	Std Dev	Minimum	Number	Mean	Std Dev
Cedarview & Jockvale	0.63	111	1.33	0.34	0.67	148	1.37	0.34
Beatrice & Longfields	0.77	45	1.41	0.31	0.73	97	1.49	0.33
Berrigan & Longfields	0.63	206	1.36	0.35	0.53	421	1.37	0.33
Portobello & Brian Coburn	0.80	71	1.42	0.36	0.60	201	1.36	0.37
Stonehaven & Bridgeston	0.60	150	1.38	0.37	0.77	247	1.38	0.32
All five roundabouts	0.60	583	1.37	0.35	0.53	1,114	1.38	0.34

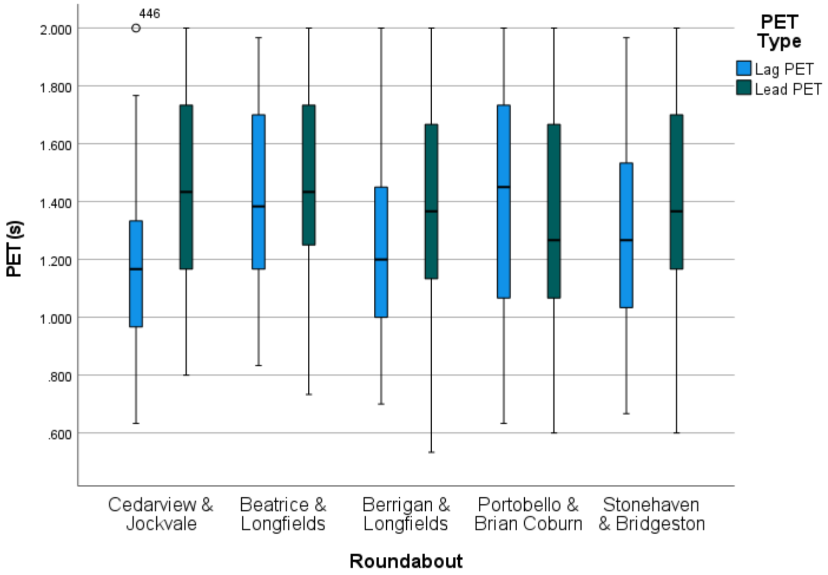

Figure 2: Boxplot of PET values of all conflicts (PET ≤ 2s).

The performance of each roundabout was evaluated to compare the risk of conflicts at each approach of the roundabout. This analysis used the ratio of number of PET conflicts to traffic volume as an exposure factor. Three traffic volumes were considered to create two exposure factors of each quarter:

$$Risk\ Ratio\ 1 = 1000 \times \frac{N}{{V_T}^2} \qquad \text{Equation 1}$$

$$Risk\ Ratio\ 2 = 1000 \times \frac{N}{V_A \times V_C} \qquad \text{Equation 2}$$

Where: N = number of PET conflicts on the approach; V_T = total traffic volume of the quarter (veh/h), which is the sum of circulating volume and approach volume; V_A = traffic volume of the approach of each quarter (veh/h); and V_C = circulating traffic volume of each quarter (veh/h).

The risk ratio results also show that the Berrigan & Longfields roundabout had the highest risk ratios among the five roundabouts followed by Stonehaven & Bridgeston. These two roundabouts also have the highest three-year collision frequency of the five roundabouts in this analysis. Based on the data for this sample of five roundabouts, the three-year collision frequency was strongly correlated to both risk ratio factors, with the strongest correlation of 0.867 and 0.863 with the off-peak values of Risk Ratio 1 and Risk Ratio 2, respectively.

6.2 Analysis of TTC at Roundabouts

For the TTC conflicts (TTC ≤ 2 s), the mean TTC values were 1.19 s and 1.25 s during peak and off-peak periods, respectively. The difference between mean TTC values was tested for the observed traffic conflicts (TTC ≤ 2 s) using the independent samples t-test and non-parametric tests and using the level of significance of 5%. For TTC conflicts (TTC ≤ 2 s), the difference between mean TTC values during peak and off-peak periods was statistically significant at three roundabouts. However, the difference was also statistically significant for all sites combined. Therefore, it is more likely that mean TTC interactions and conflicts are smaller during off-peak period due to the general trend of higher speeds with lower traffic volumes. Table 2 summarizes the main statistics of the TTC values observed for all conflicts.

Table 2: Summary of TTC statistics of all conflicts (TTC ≤ 2 s) on observed roundabouts.

Intersection	Off-Peak				Peak			
	Minimum	Number	Mean	Std Dev	Minimum	Number	Mean	Std Dev
Cedarview & Jockvale	0.60	246	1.12	0.35	0.60	355	1.22	0.39
Beatrice & Longfields	0.41	228	0.99	0.35	0.60	589	0.92	0.29
Berrigan & Longfields	0.07	388	1.28	0.55	0.60	687	1.42	0.40
Portobello & Brian Coburn	0.61	115	1.33	0.41	0.61	207	1.34	0.42
Stonehaven & Bridgeston	0.61	267	1.24	0.35	0.60	373	1.43	0.36
All five roundabouts	0.07	1,244	1.19	0.44	0.60	2,211	1.25	0.42

Similar to PET conflicts, the same two TTC risk ratios were calculated for each approach and averaged for each roundabout. In general, the values of risk ratios were close during peak and off-peak periods, and the paired *t*-test indicated that the difference was statistically insignificant for both risk ratios at 5% level of significance. Again, the two roundabouts with the highest three-year collision frequencies (Berrigan & Longfields and Stonehaven & Bridgeston) had the highest risk ratios among the five roundabouts. Using this sample of five roundabouts, the three-year collision frequency was correlated to both risk ratio factors in the off-peak period but the correlation coefficients of 0.590 and 0.551 (with Risk Ratio 1 and Risk Ratio 2, respectively) are lower than those for PET conflict frequency.

6.3 Analysis of TTC at RLC and Reference Intersections

After processing the video data on five RLC (treated) and five reference (untreated) sites using the T-Analyst software and extracting the vehicles' trajectories, a MATLAB script was used to process the trajectories to find the minimum TTC for rear-end conflicts (TTC). The incidents of TTC less than to 2 s were considered as conflicts. Table 3 provides a summary of the number of rear-end TTC conflicts and observed vehicles in peak and off-peak periods of video data collection at each site. All numbers in this table correspond to one approach at each intersection, where the approach monitored by the RLC was selected for the treated sites. To account for traffic volume differences at each site, the ratio of conflicts to number of observed vehicles was calculated for each site.

Table 3: Number of rear-end TTC conflicts (TTC ≤ 2 s) and observed vehicles at treated and untreated sites.

Location	Peak period			Off-peak period		
	Number of conflicts	Number of observed vehicles	Proportion	Number of conflicts	Number of observed vehicles	Proportion
Treated sites						
Coldrey Ave & Kirkwood Ave	10	401	0.025	5	218	0.023
Heron Rd & Riverside Dr	368	1,387	0.265	17	510	0.033
Innes Rd & Orléans Blvd	42	578	0.073	23	334	0.069
Ogilvie Rd & St. Laurent Blvd	263	1,758	0.150	173	1,380	0.125
Tenth Line Rd & St. Joseph Blvd	49	1,140	0.043	27	680	0.040
All treated sites	732	5,264	0.139	245	3,087	0.079
Untreated sites						
Albion Rd N & Walkley Rd	41	676	0.061	21	521	0.040

Alta Vista Dr & Smyth Rd	21	469	0.045	8	306	0.026
Baseline Rd & Woodroffe Ave	76	1,413	0.054	56	899	0.062
Montréal Rd & Ogilvie Rd	101	851	0.119	57	516	0.110
Woodroffe Ave & Georgina Dr	26	823	0.032	8	359	0.022
All untreated sites	265	4,232	0.063	150	2,601	0.058

The table shows that the treated sites had higher proportions of conflicts in relation to observed vehicles during peak and off-peak periods. The difference between the ratio of conflicts to observed vehicles at treated and untreated sites was tested using the Chi-square test and test of proportions in SPSS software. The Chi-square test is a non-parametric test for evaluating significant differences between group frequencies, and the independent-samples proportions test compares two independent proportions. Both tests showed that the difference between the treated and untreated sites was statistically significant at a 5% significance level during peak and off-peak periods. Therefore, the results suggest that the RLC treatment increases the probability of vehicles experiencing a rear-end TTC conflict. The difference between the proportions during peak and off-peak periods was also tested for each site. The results indicated that there was no significant difference in the proportion of vehicles with TTC conflict on all intersections except for the treated site Heron Rd & Riverside Dr.

The highest TTC proportions were experienced at the Heron Rd & Riverside Dr intersection, which also experienced the highest average annual collision frequency after treatment. Finally, linear correlation for the TTC proportion at peak and off-peak periods and collision frequencies at eight (five treated and three untreated) sites, for which collision data were available, showed strong to moderate correlations between TTC proportions in the peak period and the frequencies of single motor vehicle (SMV), property damage only (PDO), and total collisions, with the corresponding values of 0.690, 0.568, and 0.501, respectively. Also, a correlation of 0.693 was found between sideswipe collisions and TTC proportions in the off-peak period.

6.4 Analysis of Deceleration at RLC and Reference Intersections

The deceleration rate was collected for all vehicles approaching each observed intersection in the yellow and red intervals. Because the trajectory of each vehicle encompassed multiple measurements of position, speed, and deceleration, the surrogate measures extracted for each vehicle were the maximum and mean deceleration rates. The maximum and mean deceleration rates corresponding to each vehicle were averaged to calculate the average mean and average maximum deceleration at each site, as shown in Table 4. As the table also indicates, the treated sites had higher average mean and maximum deceleration values than the untreated sites during peak and off-peak periods.

Table 4: Deceleration rate (m/s^2) at RLC treated and untreated sites.

Location	Mean deceleration[1]		Maximum deceleration[1]	
	Peak	Off-peak	Peak	Off-peak
Treated sites				
Coldrey Ave & Kirkwood Ave	1.672	1.873	4.030	4.485
Heron Rd & Riverside Drive	1.482	2.779	4.120	7.658
Innes Rd & Orléans Blvd	1.722	1.757	4.932	4.816
Ogilvie Rd & St. Laurent Blvd	1.513	1.563	4.518	4.661
Tenth Line Rd & St. Joseph Blvd	2.421	2.574	6.984	7.355
All treated sites[2]	1.686	1.898	4.869	5.469
Untreated sites				

Albion Rd N & Walkley Rd	1.253	1.288	3.363	3.494
Alta Vista Dr & Smyth Rd	1.507	1.489	4.269	4.184
Baseline Rd & Woodroffe Ave	1.307	1.456	3.354	3.710
Montréal Rd & Ogilvie Rd	1.522	1.576	4.250	4.454
Woodroffe Ave & Georgina Dr	1.443	1.591	4.257	4.803
All untreated sites[2]	1.393	1.475	3.790	4.004

[1] Positive deceleration values correspond to negative acceleration or reduction in speed.

[2] Average values for each set of sites are calculated by averaging the measures for individual vehicles and are therefore different from averaging the values for the individual sites in this table.

The test of normality of Kolmogorov-Smirnov and Shapiro-Wilk in SPSS at each site was used to determine whether deceleration values at each site follow a normal distribution. The results indicated that the deceleration rates (mean or maximum) were mostly not normally distributed. The significance of average mean and maximum deceleration value differences at treated and untreated sites was tested using independent samples *t*-test and non-parametric tests in SPSS. The results of both tests indicated that the differences are statistically significant at 5% level of significance. Therefore, the results confirm that drivers adopt higher deceleration values at RLC-treated approaches compared to other approaches with no RLC.

The significance of these differences was also tested between peak and off-peak periods at each site. Mixed results were obtained at individual sites, but a statistically significant difference was evident when comparing the values for each set of sites combined (all treated and all untreated). Thus, the deceleration rates were higher during off-peak hours in comparison to peak hours in both treated and untreated sites. Therefore, the highest deceleration rates were observed at treated sites during off-peak hours. The highest deceleration rates were experienced at the Heron Rd & Riverside Dr intersection, which also experienced the highest average annual collision frequency after treatment. Again, linear correlation for the deceleration measures at peak and off-peak periods and collision frequencies at the eight sites with available collision data showed moderate to strong correlation between mean deceleration in the peak period and each of rear-end, sideswipe, PDO, and total collision frequencies. These correlation coefficients were 0.502, 0.489, 0.584, and 0.559 respectively.

7 Segment Treatment Results

The upstream and downstream areas for each speed camera and DSDS were defined by finding the location where the drivers notice the treatment. For easy reference, these areas are referred to as upstream and downstream of treatment. The speed measures were estimated upstream and downstream of treatment for each site. The number of vehicles complying with the speed limit was also compared from upstream to downstream of the treatments. As mentioned earlier, because the road centreline signs are installed in the spring/summer and removed in the fall/winter, data were collected at the same sites before and after installation and the trajectories were further processed to find the speed profiles of the vehicles travelling at each of the five locations before and after treatment.

7.1 Speed Camera

Speed cameras in Ottawa are installed on one side of the road such that vehicles in the travel direction closer to the speed camera are targeted from the rear. It is not clear whether the speed cameras in Ottawa also target the vehicles in the direction of travel farther away from the camera. The analysis for speed cameras considered only this direction of travel that is closer to the speed camera. The speed profiles of individual vehicles were found for all locations. Figure 3 shows an example of the vehicles' speed profiles at one selected speed camera location. The speed camera location is set at zero distance such that vehicle positions before the speed camera show in the figure as negative distances, and vice versa.

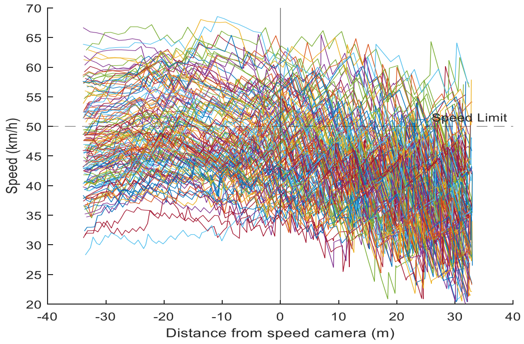

Figure 3: Speed profiles at Katimavik Rd speed camera.

Table 5 summarizes the speed measures at each site. According to the table, there is a general trend of speed reduction as the vehicles approach the influence area of the speed cameras. The percentage of speed reduction at each site ranges from 9% to 17% for mean speed and from 5% to 12% for the 85th percentile speed. Using the *t*-test of independent samples and non-parametric tests to test the significance of the difference in speeds before and after the camera location, all sites showed that this difference was statistically significant at a 5% level of significance. Also, using the one-sample *t*-test and Wilcoxon Signed Rank (non-parametric) test, it was shown that the mean speeds at the speed camera sites were significantly lower than the speed limit, while the 85th percentile speeds were not significantly different from the speed limit.

It is also noted that the value of the speed reduction may be impacted by drivers who are familiar with the area and may have reduced their speeds before reaching the analysis area. Also, some drivers may adopt a speed within 5 or 10 km/h higher than the speed limit expecting that a speeding ticket is normally issued after such an increment. Therefore, the compliance rates of vehicles travelling within the speed limit and within different increments above the speed limit can be a good indicator of the speed cameras' effectiveness. As shown in the table, most vehicles at four sites were travelling within the speed limit and close to 90% were travelling within 5 km/h above the speed limit. The lowest compliance rate was at the Longfields Dr site but even this one showed an increase of nearly 20% in the speed limit compliance rate and 12% increase within the proportion of vehicles within 5 km/h of the speed limit.

Table 5: Summary of speed results at speed camera sites.

Location	Innes Rd	Katimavik Rd	Longfields Dr	Ogilvie Rd	Watters Rd
Speed limit (km/h)	60	50	40	60	40
Number of vehicles	552	153	124	426	426
Speed measures upstream treatment					
Mean speed (km/h)	64.7	47.2	53.8	67.4	40.5
V_{85} (km/h)	72.1	56.1	60.9	77.0	45.6
Compliant	32.1%	64.1%	18.5%	19.2%	19.2%
≤5	25.0%	15.7%	13.7%	18.5%	18.5%
≤10	22.6%	13.1%	26.6%	23.9%	23.9%
≤20	18.8%	7.2%	41.1%	38.3%	38.3%
Speed measures downstream treatment					
Mean speed (km/h)	58.8	41.6	44.6	58.0	36.6

V_{85} (km/h)	67.2	49.4	52.3	73.0	41.1
Compliant	73.2%	82.4%	37.9%	69.2%	69.2%
≤5	13.8%	9.2%	25.8%	20.2%	20.2%
≤10	5.3%	2.6%	12.9%	8.0%	8.0%
≤20	6.3%	5.9%	23.4%	2.6%	2.6%
Change from upstream to downstream					
Mean speed (km/h)	-5.8	-5.6	-9.2	-9.4	-3.9
V_{85} (km/h)	-4.9	-6.7	-8.6	-4.1	-4.5
Compliant	41.1%	18.3%	19.4%	50.0%	50.0%
≤5	-11.2%	-6.5%	12.1%	1.6%	1.6%
≤10	-17.4%	-10.5%	-13.7%	-16.0%	-16.0%
≤20	-12.5%	-1.3%	-17.7%	-35.7%	-35.7%
Percentage change from upstream to downstream					
Mean speed	-9.0%	-11.9%	-17.0%	-13.9%	-9.5%
V_{85} (km/h)	-6.8%	-12.0%	-14.1%	-5.3%	-9.9%

V85 = 85th percentile speed; Compliant = percentage of vehicles not exceeding the speed limit; ≤5, ≤10, and ≤20 = percentage of vehicles within 5, 10, and 20 km/h above speed limit, respectively; change from upstream to downstream is calculated as the value of the measure downstream minus the corresponding value upstream; and percent change from upstream to downstream is calculated as the change in each measure divided by the value upstream.

7.2 DSDSs

A DSDS is installed on one side of the road facing the direction of travel closer to the DSDS. Thus, it is relevant mainly to this direction of travel closer to the DSDS, where drivers can see their vehicles' speeds. Therefore, the analysis in this section focused on the direction of travel closer to the DSDS. Figure 4 shows an example of the speed profiles of the vehicles observed at one selected DSDS location. The DSDS location is set at zero distance such that vehicle positions before the DSDS show in the figure as negative distances, and vice versa.

Like speed cameras, the mean and 85th percentile speed values were first estimated for each segment in the analysis area, then the average value for each measure is reported for the segments upstream and downstream of the treatment. Table 6 summarizes the speed measures at each site. The table shows a trend of speed reduction due to treatment, but the extent of this reduction is smaller than that of speed cameras. While the percentages of reduction in mean and 85th percentile speed are relatively close to those experienced by speed cameras, the rates of speed compliance are much lower than those of the speed cameras, and the proportions of vehicles at the higher speed increments above speed limit are higher for DSDSs. Both the one-sample *t*-test and Wilcoxon Signed Rank (non-parametric) test showed that both the mean and 85th percentile speeds at the DSDS sites were significantly higher than the speed limit at 5% level of significance.

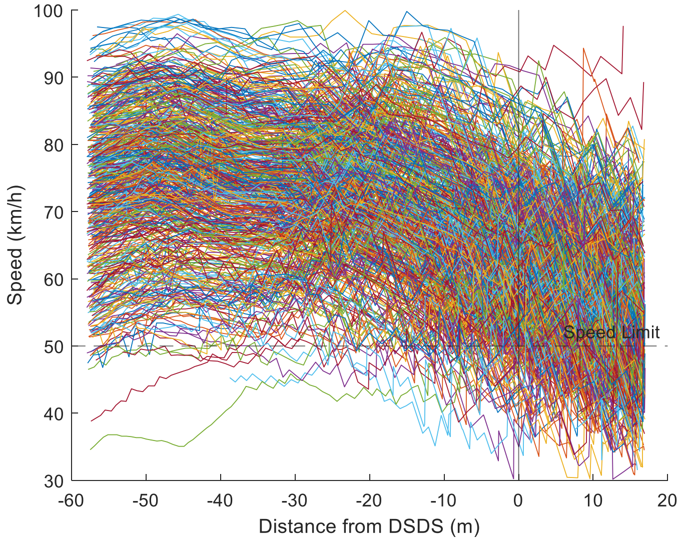

Figure 4: Speed profiles at the St. Laurent Blvd DSDS.

Table 6: Summary of speed results at DSDS sites.

Location	Cumming Ave	Jeanne d'Arc Blvd	Naskapi Dr	Prince of Wales Dr	St. Laurent Blvd
Speed limit (km/h)	40	60	40	50	50
Number of vehicles	119	97	20	495	647
Speed measures upstream treatment					
Mean speed (km/h)	51.7	75.4	50.8	76.2	72.0
V_{85} (km/h)	58.8	85.1	56.1	85.7	83.6
Compliant	1.7%	3.1%	0.0%	1.6%	1.1%
≤5	9.2%	7.2%	10.0%	1.2%	4.3%
≤10	28.6%	6.2%	35.0%	4.4%	6.3%
≤20	47.1%	16.5%	50.0%	30.1%	23.2%
Speed measures downstream treatment					
Mean speed (km/h)	48.3	67.7	47.3	68.1	62.4
V_{85} (km/h)	55.1	78.7	53.1	78.6	73.9
Compliant	2.5%	17.5%	5.0%	6.3%	7.4%
≤5	27.7%	20.6%	30.0%	10.9%	13.1%
≤10	29.4%	16.5%	30.0%	18.8%	16.2%
≤20	37.0%	39.2%	30.0%	38.0%	36.9%
Change from upstream to downstream					
Mean speed (km/h)	-3.4	-7.7	-3.5	-8.1	-9.6
V_{85} (km/h)	-3.8	-6.3	-3.0	-7.1	-9.7
Compliant	0.8%	14.4%	5.0%	4.6%	6.3%
≤5	18.5%	13.4%	20.0%	9.7%	8.8%
≤10	0.8%	10.3%	-5.0%	14.3%	9.9%
≤20	-10.1%	22.7%	-20.0%	7.9%	13.8%
Percentage change from upstream to downstream					

Mean speed	-6.6%	-10.2%	-7.0%	-10.6%	-13.3%
V_{85} (km/h)	-6.4%	-7.4%	-5.3%	-8.3%	-11.6%

V85 = 85th percentile speed; Compliant = percentage of vehicles not exceeding the speed limit; ≤5, ≤10, and ≤20 = percentage of vehicles within 5, 10, and 20 km/h above speed limit, respectively; change from upstream to downstream is calculated as the measure downstream minus the same measure upstream; and percent change from upstream to downstream is calculated as the change in each measure divided by the value upstream.

7.3 Road Centerline Signs

For speed analysis, the mean and 85th percentile speed values were estimated for each location in the before and after periods. the trajectories were further processed to find the speed profiles of the vehicles travelling at each of the five locations before and after treatment. Figure 5 shows an example of the speed profiles of the observed vehicles at one site before and after treatment. Table 7 presents a summary of the speed measures at each site.

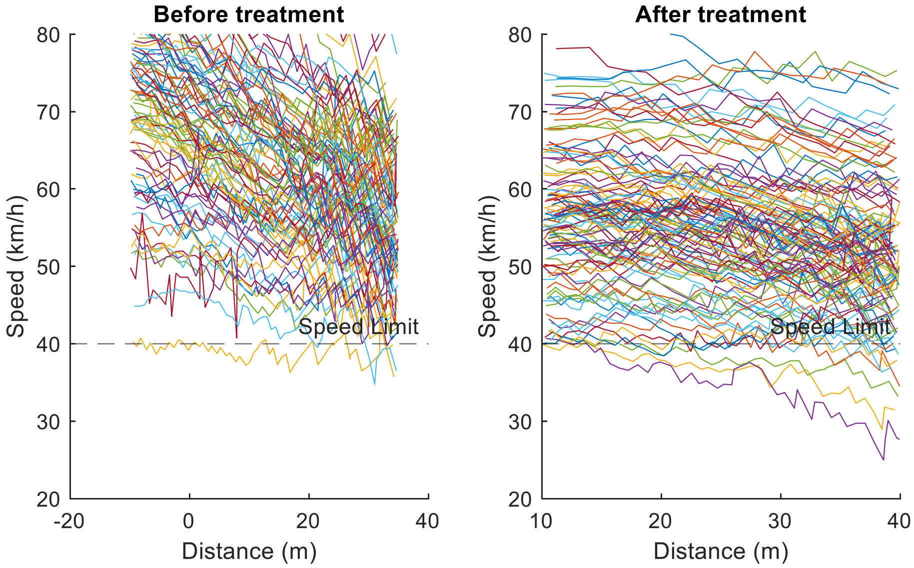

Figure 5: Speed profiles at the Maxwell Bridge Rd centerline signs.

The table show a general trend of speed reduction after treatment at most sites, while the Chesterton Dr site is an exception to this trend. On the other four sites, the reduction in mean and 85th percentile speeds ranged from 4% to 16%. The difference in speeds at these four sites was found to be statistically significant at 5% level of significance using the *t*-test of independent samples and non-parametric tests. Both the one-sample *t*-test and Wilcoxon Signed Rank (non-parametric) test showed that both the mean and 85th percentile speeds at the sites with road centerline sites were not significantly different from the speed limit at 5% level of significance. The rate of compliance with speed limits increased at 3 sites with a range of 13% to 23%. The site with the highest speed limit experienced a 55% increase in the compliance rate with speed limit.

Table 7: Summary of speed results at road centerline sites.

Location	Canyon Walk Dr	Chesterton Dr	Cresthaven Dr	Knoxdale Rd	Maxwell Bridge Rd
Speed limit (km/h)	50	40	40	40	40
Speed measures before treatment					
Number of vehicles	66	76	76	136	96
Mean speed (km/h)	51.8	35.3	52.4	48.8	62.0
V_{85} (km/h)	59.0	42.3	62.1	57.0	74.1
Compliant	30.3%	75.0%	31.6%	32.4%	9.4%
≤5	25.8%	11.8%	25.0%	14.0%	10.4%
≤10	24.2%	7.9%	18.4%	11.0%	12.5%
≤20	10.6%	5.3%	21.1%	6.6%	36.5%
Speed measures after treatment					
Number of vehicles	40	83	61	125	109
Mean speed (km/h)	43.4	35.3	49.3	44.6	53.4
V_{85} (km/h)	50.0	41.8	59.5	52.5	62.6
Compliant	85.0%	69.9%	44.3%	55.2%	22.9%
≤5	12.5%	15.7%	21.3%	8.8%	22.0%
≤10	2.5%	9.6%	19.7%	5.6%	11.9%
≤20	0.0%	4.8%	13.1%	1.6%	13.8%
Change from before to after treatment					
Mean speed (km/h)	-8.4	0.0	-3.1	-4.2	-8.6
V_{85} (km/h)	-9.0	-0.5	-2.6	-4.6	-11.5
Compliant	54.7%	-5.1%	12.7%	22.8%	13.6%
<=5	-13.3%	3.8%	-3.7%	-5.2%	11.6%
<=10	-21.7%	1.7%	1.3%	-5.4%	-0.6%
<=20	-10.6%	-0.4%	-7.9%	-5.0%	-22.7%
Percent change from before to after treatment					
Mean speed	-16.2%	0.0%	-5.9%	-8.5%	-13.8%
V_{85} (km/h)	-15.2%	-1.2%	-4.2%	-8.0%	-15.6%

V_{85} (km/h)= 85th percentile speed; Compliant = percentage of vehicles not exceeding the speed limit; ≤5, ≤10, and ≤20 = percentage of vehicles within 5, 10, and 20 km/h above speed limit, respectively; change from before to after treatment is calculated as the measure after treatment minus the same measure before treatment; and percent change from before to after treatment is calculated as the change in each measure divided by the value before treatment.

8 Conclusions

Conflicts at roundabouts were defined as those interactions with PET or TTC value up to a threshold of 2 s. Risk ratios were calculated as the ratio between the frequency of each conflict type and the traffic volume exposure. It was shown that for the selected sample of five roundabouts, the sites with the highest collision frequencies had the largest risk ratios. A linear correlation was also found between the number of collisions at each site and these risk ratios, especially those found in the off-peak period. While the underlying assumptions of linear correlation are not consistent with the statistical distribution of collision frequency, the positive and relatively strong correlations confirm the potential of these risk ratios in assessing the expected level of safety at a roundabout.

For RLCs, the results showed significantly higher proportions of TTC conflicts (frequency of vehicles with TTC value up to a 2-s threshold to total number of vehicles) and higher deceleration rates on the RLC approaches, which is expected to increase the probability of rear-end collisions. Furthermore, the deceleration rates were higher during off-peak hours in comparison to peak hours in both treated and untreated sites. Linear correlation between the conflict measures and collision frequencies indicated moderate to strong positive correlations between the TTC proportions and deceleration rates and frequencies of different collision categories.

The speed cameras, DSDSs, and road centreline signs are the segment safety treatments assessed in this study. The results indicated that speed reductions were associated with all treatments, the DSDS sites generally had the highest speeds as indicated in the ratio of mean and 85th percentile speeds to the speed limit. DSDS sites also had mean and 85th percentile speeds that were statistically higher than the speed limit. The road centerline sites varied in their performance with the 85th percentile speed ranging from around 130% to nearly 160% of the speed limit. On the other hand, speed camera sites had 85th percentile speeds that were generally close to 100% of the speed limit except for one site. Statistical testing of the differences indicated that the proportions of mean and 85th percentile speeds to speed limit at the speed camera sites were significantly different from those at DSDS sites but not from those at the road centerline sites. However, the relatively small sample size may have contributed to the lack of significant difference between speed camera sites and road centerline sites. The results also showed that the lowest speed reduction due to the treatment were observed at the road centerline sites. On the other hand, speed reductions seemed to be comparable at speed camera and DSDS sites. However, the differences were statistically significant indicating that speed reductions at speed camera sites were likely higher than those at the other treatments and the observed differences were not caused by random variations alone.

The speed analysis also showed that the compliance rates (proportion of vehicles driving below speed limit or within a specific increment above speed limit) were considerably lower at DSDS sites compared to both speed camera and road centerline sites, and the differences were statistically significant. Therefore, it can be concluded that the rates of compliance with speed limit or speed limit plus an increment were highest at speed cameras followed by road centerline treatments.

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