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Lesson learned from the application of intersection safety devices in Edmonton

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ABSTRACT

The City of Edmonton began its intersection safety device (ISD) program in 2009 with the installation of 50 cameras throughout the city. The ISDs are approach-specific and combine automated enforcement of red-light running and speed violations during the red and green phases of the intersection control. The goal of this study is to evaluate the safety performance of ISDs within the city of Edmonton, Canada and to identify factors that can lead to successful selection of future ISD sites. A before-and-after Empirical Bayes (EB) method is used to account for regression-to-the-mean and other confounding factors. A safety performance function and yearly calibration factors are developed using data from a set of reference intersections within Edmonton. The before-and-after analysis is applied at the overall intersection level and for each approach of the ISD intersections. The results showed significant reductions that ranged from 12% to 25% for total collisions, and from 33% to 43% for angle collisions. No significant reduction was observed for severe collisions at the intersection level, however significant reductions were found at the approach level at locations with a relatively higher collision history. The impact of site selection criteria on collision reduction was also evaluated. Greater reductions were found at sites with a higher collision frequency. Additionally, the impact of intersection characteristics on collision reduction was investigated. Speed limits, presence of separated right turn lane and the number of lanes were found to impact ISD collision reduction.

1. Introduction

The City of Edmonton, in Alberta, Canada, introduced Intersection Safety Devices (ISD), which combine red-light running enforcement and speed enforcement at intersections in 2009. Both red-light running and speeding are major contributors to collisions at intersections. In 2014 there were nearly 25,000 collisions in the city of Edmonton including over 2900 injuries and 23 fatalities. Collisions at intersections accounted for 55% of the total number of collisions and 68% of injury collisions. The two main causes of injury collisions at intersections were rear-end collisions and left-turn cross path collisions (Motor vehicle collisions, 2014).

Angle collisions and rear-end collisions are the commonly identified collisions related to red-light running (Council et al., 2005). Angle collisions occur when a vehicle enters the intersection after the onset of the red phase and collides with a vehicle with the right of way entering from a perpendicular roadway. In the literature, red-light cameras (RLC) are commonly found to be associated with an increase in rear-end collisions. The increase in rear-end collisions can be attributed to drivers stopping suddenly or slowing at the onset of the yellow phase to avoid RLC ticketing, while the following vehicle speeds up as it plans to proceed through the intersection.

The effectiveness of RLCs has been extensively investigated in the literature. However, the safety impacts of ISDs have not been as widely studied. Although ISDs are similar to RLCs, the addition of speed enforcement should have an influence on the intersection's safety performance. Speeding increases both the odds of being involved in a collision as well as the risk of injury or fatality resulting from a collision (Elvik, 2005). This could be attributed to the fact that when driving at higher speeds, drivers have less time to react to changing conditions, and stopping distances are increased. Furthermore, the criteria used to determine ISD locations had not been well defined or studied. ISD performance is likely affected by various intersection characteristics. Understanding the factors that impact ISD performance will help when developing future ISD programs.

Previous studies have been mainly focused on RLCs. RLC target collisions related to red-light running violations, but not specif-

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ically speed. The results of these RLC studies have varied, but generally show a decrease in angle collisions and an increase in rear-end collisions. A *meta*-analysis (Høye, 2013) looked at the impact of RLC cameras across 28 RLC studies. Overall the results showed a 39% increase in rear-end collisions, a 19% increase in rear-end injury collisions and a 33% decrease in right-angle collisions. A study by (Sayed and de Leur, 2007) evaluated the performance of RLC in the city of Edmonton. The study included 25 intersections with RLCs installed between 1999 and 2003. Significant reductions were observed in all collision categories, including an 11% reduction in total collisions, 17% reduction in angle collisions and 12% reduction in rear-end collisions. The temporal changes of collision reductions following RLC installation was observed by Wang et al. (2015). The changes in collision modification factors (CMF) were predicted using ARMA time series analysis. The CMFs were determined for a period of 36 months. It was observed that CMFs for total collisions were lower in the first 9 months and then started to increase. Similar trend was observed for Fatal+Injury collisions, the CMF was lower for the first 18 months compared to the entire 36 months.

A study of ISDs in Victoria, Australia was conducted by (Budd et al., 2011). Their study included 77 intersection locations in Victoria. Warning signs were posted at all intersection approaches however cameras were limited to only 1 or 2 approaches per intersection. A 44% reduction was found in target collisions (right angle as well as right turn collisions) and no significant change in rear-end collisions. The study also found there was a strong effect on the targeted approaches; there was a 26% reduction in fatality collisions at intersections and a 47% reduction at target approaches.

A study of Winnipeg's intersection photo enforcement program which captured speed on green and red-light-running was conducted by (Vanlaar et al., 2014). The study looked at both the changes in collisions as well as speeding and red-light running violations. There was a drop in both speed and red-light running violations, however the reduction in speeding violations were greatest for less severe violations (1–13% over the speed limit) and less effective at reduction serious speeding violations (more 13% over the speed limit). Right angle collisions were found to decrease 46% but there was no change in collisions relating to speeding. Rear-end collisions were found to increase by 42% however time series analysis suggested that rear-end collisions may decrease over time.

A study by Alberta Transportation evaluated the safety performance of 54 ISD equipped intersections in four municipalities in Alberta (Zarei and Izadpanah, 2014). A before-and-after evaluation was conducted using the EB method. The study investigated the change in collisions and collision severity following ISD installation. Overall the study found a 1% increase in total collisions. The largest reductions were in severe and angle collisions (32% and 31% respectively). The study also found increases in the number of PDO and rear-end collisions (11% and 9%).

(De Pauw et al., 2014) analysed the change in injury collisions after the installation of ISDs in Flanders, Belgium using a before-and-after Empirical Bayes methodology. The study included 253 intersections and a comparison group which included all collisions in Flanders. The total injury collisions increased 5% to 9% after the installation of the cameras. The results also indicated a 14% to 18% reduction in severe side angle collisions and a 44% increase in rear-end collisions. The increase in rear-end collisions was much greater in urban areas than rural areas. The study also found that the proximity of ISDs impact the safety effectiveness; when there were 2 or more ISDs within 1500 m the collisions reductions were smaller.

Overall, the current literature suggests that ISDs are effective in reducing angle collisions. The changes in rear-end collisions have varied, from large increases to non-significant decreases. However, there are still a few issues regarding the safety of ISDs that need to investigated. Consequently, the first objective of this study is to estimate the traffic safety impact of ISDs using data about the City of Edmonton's ISD program. The safety evaluation is conducted using the Empirical Bayes (EB) before-and-after analysis technique, as outlined in the Highway Safety Manual (2010). The EB method is considered the state-of-the-art technique to evaluate safety countermeasures. Since ISDs are installed on specific approaches, the safety evaluation is repeated twice, once at the approach level (i.e., each leg of the signalized intersection is analyzed separately) as well as the intersection level as a whole. For the approach level analysis, collisions are aggregated for each leg of the intersection. It is important to note that ISD are installed separately at each approach. For example, some intersection might have an ISD on only one of its four legs, or ISD could be available on all four legs. Fig. 1 shows an example of an intersection with ISDs installed on two approaches. For the intersection level analysis, collisions are aggregate for the whole intersection. Most ISD intersections have enforcement signs installed on all four legs. One of the advantages of conducting an approach level analysis is being able to examine the safety effects of approaches with signs only versus approaches with both signs and ISDs.

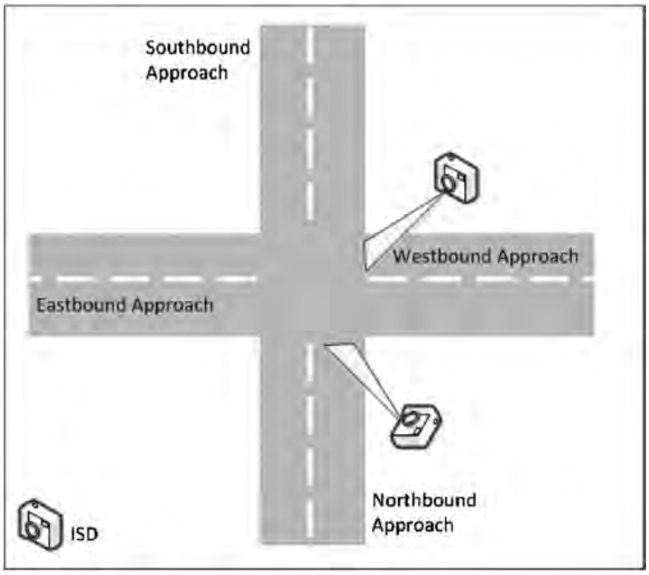

Fig. 1. Sample ISD intersection.

The second objective of this study is to identify factors that can lead to a successful selection of future ISD sites. Current studies do not differentiate between successful and ineffective ISD implementations. It is to be expected that ISD performance will not be the same for all sites. There may be other traffic and geometrical factors that contribute to a successful ISD application. If a relationship between collision reductions and intersection characteristics can be established at enforced sites it can be used to refine the selection of future ISD sites.

2. Program and data description

The first ISDs were installed at three intersections in 2009 and expanded to 50 approaches at 30 arterial intersections in the following years. ISDs are not always located on every approach to an intersection; some intersections have only one approach with an ISD and some have multiple. Drivers are made aware of the presence of ISDs, all intersection approaches with an ISD have a sign posted warning of automated enforcement. Additionally, drivers can view a list of all ISD equipped intersections that is available on the City of Edmonton website. The locations for ISD sites were cho-

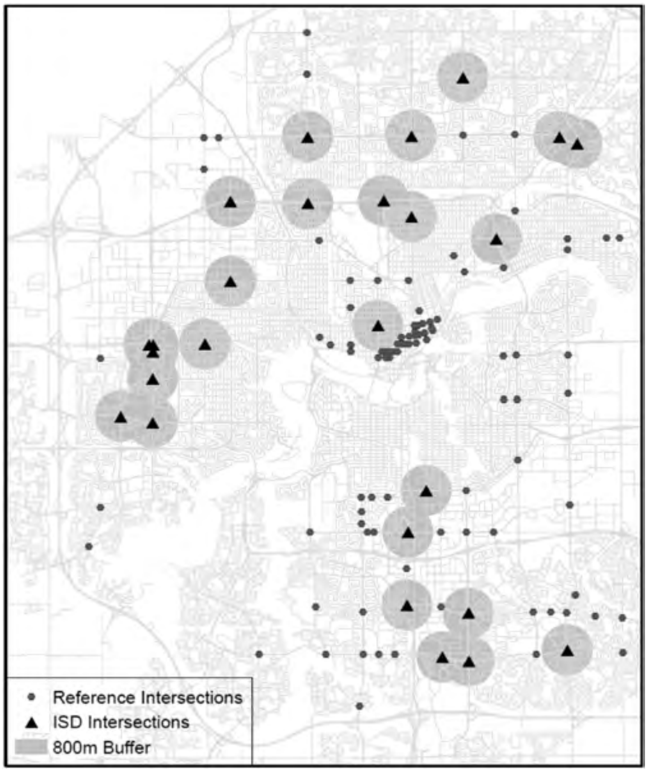

Fig. 2. ISD locations.

sen based on sites that exhibited high numbers of total collisions and angle collisions.

The study period spans from January 2006 to December 2013. Average Annual Daily Traffic (AADT) and collision history were collected for each year of the study period. Intersection characteristics, such as the number of lanes, speed limits, and lane configuration, were also collected. Cameras were installed between 2009–2011, a buffer period of one year following the camera installation was not included in the after period. The before period at each intersection ranged from 3 to 5 years and the after period ranged from 2 to 4 years depending on the installation date of the camera. Data were gathered for two distinct groups: the treatment group, which was made up of the 50 ISD-equipped intersections, and the reference group, which consisted of 93 signalized intersections. The reference group is made up of signalized intersections without ISDs, and in order to avoid potential spillover effects in the reference group a buffer of 800 m was used to ensure that the reference intersections were not close to the treated sites. Fig. 2 show the location of the ISD equipped intersections as well as the reference sites. Data were collected at the intersection level as well as at the approach level.

The City of Edmonton maintains a Motor Vehicle Collision Information System (MVCIS), which is a database of police-reported vehicular collisions within the city. Reportable collisions are those that occur on public roads including at least one motor vehicle, and result in an injury, fatality, or property damage of at least $2000 CAD. Collisions are categorized by the roadway location, and can occur at an intersection or midblock. Intersection collisions are defined as occurring within the area extending 10 m (m) past the legally defined limits of the outer crosswalk lines of intersecting roadways. The collision database includes reported details for each collision, such as collision severity, time of day, travel direction, etc. For the ISD evaluation, one key component of the database was the reported collision cause; in particular, the collision cause “follow-to-closely” was used to identify rear-end type collisions. Based on the data provided, five collision classifications were used in the analysis which are described in Table 1.

Table 1
Description of ISD collision classifications.

Collision Classification	Description
Total	Includes all collisions
Severe	Includes all fatal and injury collisions
Property Damage Only	Includes all property damage only collisions
Angle	Includes collisions involving at least 2 vehicles traveling on perpendicular approaches and traveling through the intersection
Rear-End	Includes all collisions with collision cause classified as followed too closely

3. Methodology

3.1. Safety performance functions

Safety performance functions (SPF) are used in collision prediction to relate the collision frequencies to the traffic volumes and other explanatory variables. SPFs are used to predict the collision frequency at treated locations, which is a key component of the before-and-after evaluation process. In this study, a negative binomial (NB) model is used since the negative binomial error structure is able to capture the over dispersion in the collision data. The model parameters were estimated using the SAS GENMOD SAS (2012) procedure, which uses maximum likelihood estimation. The scaled deviance (SD) and Pearson $\chi 2$ were used to assess the model's goodness of fit.

SPF functions were developed for each of the collision classifications at the intersection level as well as the approach level. The chosen model form for collisions was the same for both the intersection level and the approach level, and is shown in Eq. (1). A number of independent intersection-related variables were included in the analysis, and only significant variables were included in the final model. The variable selection was conducted using a backward stepwise elimination process.

$$Collisions\ \ per\ year = \mathrm{AADT}_{major}\beta_1 \times \mathrm{AADT}_{minor}\beta_2 \times \exp^{(\beta 0+\beta 3\times X1+\beta 4\times X2\ldots)} \quad (1)$$

Where,

$\mathrm{AADT}_{\mathrm{major}}$ is the AADT on major roads;
$\mathrm{AADT}_{\mathrm{minor}}$ is the AADT on minor roads; and
X_{i} represents the various geometric independent variables.

SPFs were developed using a set of reference locations that do not have ISDs installed. The selection of suitable reference groups is important to ensure the SPF predictions accurately represent what is happening at treatment sites. The reference group in this study is made up of intersections similar to the treatment site. The reference group was chosen from arterial intersections and selected based on traffic volumes, collision frequency, and geometric features. The availability of traffic volume data was a limiting factor in the selection of reference group sites.

3.2. Yearly calibration factors

Confounding factors such as weather patterns, engineering initiatives, and general traffic safety trends lead to annual fluctuations in collision frequency that cannot be entirely captured by SPFs (Persaud and Lyon, 2007). Yearly Calibration Factors (YCF) is used to address annual fluctuations that are not attributed to variables in the SPFs. The YCFs are calculated as a ratio between the number of observed collisions and the number of predicted collisions for each year at the reference sites, as shown in Eq. (2). The yearly collision frequency predicted by the SPF is adjusted through multiplying the SPF-predicted collision frequency by the corresponding YCF. This assumes that the impact of the confounding factors is similar across all sites in both the reference and treatment groups; therefore, the variations that occur at the reference sites can be assumed to occur at the treatment sites as well

$$C_i = \frac{\sum_{ref} N_i}{\sum_{ref} \mu_i} \tag{2}$$

Where,
C = yearly calibration factor
N = observed number of collisions
μ = predicted average number of collisions
i = year

k = negative binomial over-dispersion parameter (estimated from SPF).

In order to account for variations in traffic volume and difference period length a ratio of the predicted before collisions to after collisions is used as a multiplier. The expected number of collisions in the after period is then determined as the product of the multiplier and the expected number of collisions in the before period. Finally the overall odds ratio of collision reduction and the associated standard error are calculated shown in Eqs. (5)–(7). The percent reduction is then calculated from the odds ratio. The ratio of the percent reduction and its standard error is used to test significance.

$$\theta = \frac{\sum\limits_{Allsites} N_{Observed,A} / \sum\limits_{Allsites} N_{Expected,A}}{1 + Var\left(\sum\limits_{Allsites} N_{Expected,A}\right) / \left(\sum\limits_{Allsites} N_{Expected,A}\right)^2} \tag{5}$$

$$Var\left(\sum AllSitesN_{Expected,A}\right) = \sum_{AllSites}\left[\left(\frac{N_{Predicted,A}}{N_{Predicted,B}}\right)^2 \times N_{Expected,B} \times (1-\omega)\right] \tag{6}$$

$$SE(\theta) = \sqrt{\frac{\left(\sum\limits_{Allsites} N_{Obsesrved,A} / \sum\limits_{Allsites} N_{Expected,A}\right)^2 \left[\frac{1}{\sum\limits_{Allsites} N_{Observed,A}} + Var\left(\sum\limits_{Allsites} N_{Expected,A}\right) / \left(\sum\limits_{Allsites} N_{Expected,A}\right)^2\right]}{\left[1 + Var\left(\sum\limits_{Allsites} N_{Expected,A}\right) / \left(\sum\limits_{Allsites} N_{Expexted,A}\right)^2\right]^2}} \tag{7}$$

3.3. *Empirical bayes evaluation*

In order to account for regression-to-the-mean (RTM) bias, the before-and-after Empirical Bayes (EB) analysis method is used (Hauer, 1997; Hauer et al., 2002*)*. The EB method uses collision information from a reference group to address the problem of RTM. The EB method also incorporates yearly changes in traffic volume and can accommodate varying lengths for the before and after periods. Traffic safety treatment sites are generally chosen by prioritizing sites with high collision frequencies. Therefore, it is important to consider the impact of RTM bias. RTM refers to the random fluctuation in collision frequency, specifically the tendency for sites with a high collision frequency in one time period to be followed by a lower collision frequency in the following time period, and vice-versa. The safety effectiveness is the ratio of the observed number of collisions to the expected number of collisions. The first step of the EB method is to calculate the expected number of collisions in the before period for each site. The expected number of collisions is calculated as a weighted combination of the predicted number of collisions (from the SPF) and the observed number of collisions in the before period, shown in Eq. (3). The weighted adjustment factor is established using the overdispersion parameter from the SPF, as shown in Eq. (4).

$$N_{Expected,B} = (w)N_{\mathrm{Predicted,B}} + (1-w)N_{Observed,B} \tag{3}$$

$$w = \frac{1}{1 + \frac{N_{\mathrm{Predicted,B}}}{k}} \tag{4}$$

where:
w = weighted adjustment factor (between 0 and 1)
$N_{Expected,B}$ = expected number of collisions in the before period
$N_{Predicted,B}$ = predicted number of collisions in the before period
$N_{Observed,B}$ = observed number of collisions in the before period

Where;
$N_{Expected,A}$ = expected number of collisions in the after period
$N_{Predicted,A}$ = predicted number of collisions in the after period
$N_{Observed,A}$ = observed number of collisions in the after period

The percent reduction is then calculated from the odds ratio as follows; Collision reduction = 100 × $\left(1-\theta\right)$ with a standard error of 100 × SE $\left(\theta\right)$. Positive collision reduction numbers indicate a reduction in collisions, and a negative number indicates an increase in collisions. The ratio of the percent reduction and its standard error is used to test significance. If the ratio is higher than 2.0 the collision reduction percentage is significant at the 95% level.

4. Results

4.1. *Before-and-after – intersection level*

The SPF models were developed for the five collision types defined previously. The parameter estimates and the goodness of fit for the models can be seen in Table 2. Insignificant variables were removed in a backwards stepwise process to find the model with the best fit. As seen in the table the fit for the models is good and the parameters coefficient signs are intuitive. The positive value of the parameter for right-turn separation is as expected; intersections with right-turn cut-offs have been found to be associated with higher rear-end collisions in Edmonton. Significant variables in the intersection level SPF included the presence of separated right turn lanes on the minor road (0 = *not present*, 1 = *present*) and the number of approaches (1 = *4-leg intersection*, 0 = *3-leg intersection*).

The overall collision reduction percentages were established for the intersection level using the EB methodology described in the previous section. The reductions were determined for the five collision classifications outlined previously and are summarised with the standard error (SE) and EB statistical test ration in Table 3.

There were significant reductions in all the collision categories with the exception of severe collisions. For the severe collision cat-

Table 2
Intersection Level SPF Goodness of Fit and Parameter Estimate Results.

	Total Collisions	Severe Collisions	PDO Collisions	Rear-End Collisions	Angle Collisions
Parameter Estimates					
Intercept	−7.31(0.935, *<0.001*)	−9.69(0.880, *<0.001*)	−7.92(0.986, *<0.001*)	−11.57(1.234, *<0.001*)	−9.23(1.183, *<0.001*)
Major ADDT	0.47 (0.092, *<0.001)*	0.38 (0.096, *<0.001*)	0.52 (0.097, *<0.001*)	0.83 (0.121, *<0.001*)	0.35 (0.129, *0.007*)
Minor ADDT	0.55 (0.067, *<0.001*)	0.70 (0.066, *<0.001*)	0.54 (0.071, *<0.001*)	0.55 (0.083, *<0.001*)	0.66 (0.087, *<0.001*)
Right Turn Separation	0.38 (0.116, *0.001*)	–	0.41 (0.121, *<0.001*)	0.66 (0.144, *<0.001*)	–
Approaches	–	0.64 (0.163, *<0.001*)	–	–	0.98 (0.224, *<0.001*)
Goodness of Fit					
Dispersion parameter	0.16	0.12	0.17	0.23	0.27
Degrees of Freedom	89	89	89	89	89
Pearson Chi-Square	97.00	102.42	98.70	102.49	102.16
Scaled Deviance	95.15	101.23	94.88	94.03	99.06

(SE, p-value).
All variables significant at the 99% level.

Table 3
Overall Before-and-After Evaluation Results.

	Total Collisions	Severe Collisions	PDO collisions	Rear-End Collisions	Angle Collisions
% Collision Reduction (SE)	25.47 (2.06)	3.99 (6.33)	6.35 (2.99)	10.74 (3.09)	33.44 (4.98)
Statistical Test Ratio	12.36[a]	0.63	2.13[a]	3.47[a]	6.72[a]

[a] Significant at 95% level.

egory there was a small non-significant reduction. There was a 25% reduction in the total number of collisions as well as a 33% reduction in angle collisions. It is also interesting to note there was a significant 11% reduction in rear-end collisions.

Table 4 shows a summary of the changes in collision reported by other ISD evaluations. Similar to other studies our results showed a large significant decrease in the number of angle collisions. Where the results differ is in the reduction of rear-end collisions. Vanlaar et al. suggested that although there was an initial increase in rear-end collisions this may have decreased over time. The potential for change in CMF is supported by Wang et al. (2015) which showed that CMF following RLC installation fluctuated over time.

4.2. *Before-and-after evaluation – approach level*

The SPF models were developed for the five collision types defined above. The summary of the parameter estimates and the goodness of fit for the models can be seen in Table 5. As seen in the table the model's fit is good and the parameters are highly significant. Similar to the intersection level SPF, the presence of a separated right turn bay and the number of approaches were significant variables in the approach level SPF.

The EB analysis was repeated for the same set of intersections, looking at the changes in collisions at the approach level. Table 6 compares the reductions for the approaches with or without an ISD. For ISD approaches there are significant reductions in all the collision categories except for severe collisions. There was a 12% reduction in total collisions as well as a 43% reduction in angle collisions. Furthermore, there is a significant reduction in rear-end collisions (14%). The non-ISD approaches had significant reductions in the angle collisions, but non-significant changes in all other categories.

The results for the non-ISD approaches were broken down into two categories; with or without signs. Although all the ISD equipped approaches had warning signs posted, only some of the non-ISD approaches had warning signs. It was of interest to see if the approaches that did not have ISDs, but did have warning signs performed better than those without warning signs. For total collisions the results were similar for both groups. For the severe collisions there was a small reduction in collisions at the signed approaches (2%) and an increase in collisions at approaches without signs (33%), however both were non-significant. These results seem to indicate that signage without actual enforcement might not necessarily lead to improvement in safety.

4.3. *Site selection criteria*

Current ISD sites were selected based on collision history and local expertise. In order to assist agencies in identifying potential future locations for ISDs, it is of interest to appraise the current selection criteria as well as recommend new ones for the future. Site selection criteria were evaluated in two ways. Firstly, the current treatment sites were reclassified into groups according to three 'simple' site selection criteria, namely, collision frequency, collision rate, and AADT. For each criterion, the approaches were categorized into three groups based on a high, medium and low threshold. The threshold for each group was chosen to allow for sufficient samples within each group. The EB analysis was repeated for each group. The results are shown in Table 7. The thresholds for collision frequency and collision rate refer to the average yearly total collisions in the before period. The AADT is the average AADT for the before period.

The results show that generally when the collision frequency or collision rate is high, there is a larger reduction in collisions. For example, there was a significant 26% reduction in total collisions when the collision frequency was greater than 15 collisions per year in the before period. There was also a significant 29% reduction in severe collisions for locations with a high collision frequency. The influence of AADT on ISD performance is less consistent. There does not appear to be an obvious trend between sites with higher AADT numbers and collision reduction. This suggests that AADT should not be considered as an appropriate site selection criterion for future ISD placement. This is not surprising since using AADT alone would not capture other factors which would lead to higher collision numbers. Similar results for RLC have been observed in the literature; (Ko et al., 2013) evaluated the effectiveness of both collision history and AADT as site selection criteria and found that there was no identifiable trends relating changes in AADT to RLC safety effectiveness.

To further understand the best method for prioritizing ISD locations, the impact of various intersection characteristics on collision reductions was considered. Maximum likelihood linear regression models were fitted with the index of effectiveness (θ) from the EB analysis as the dependent variable, which was assumed to have a

Table 4
Summary of previous ISD research.

Study	Method	Data and Study Period	Major Findings
Alberta Transportation (2014) Canada	Before and after with Empirical Bayes	46 intersections (4 cities)	31.3% reduction in angle collisions 9.4% increase in rear-end collisions
Budd et al. (2011) Australia	Before and after with Comparison group	77 intersections Study Period: 2000–2009	44% reduction in angle collisions 26% reduction in fatality collisions No significant rear-end collisions
De Pauw et al. (2014) Belgium	Before and after with Empirical Bayes	253 intersectionsStudy Period 2000–2008	6% reduction in angle collisions 24% reduction in severe angle collision 44% increase in rear-end collisions 5% increase in injury collisions
Vanlaar et al. (2014) Canada	ARIMA time series analysis	48 intersections Study Period 1994–2008	46% reduction in angle collisions 42% increase in rear-end collisions

Table 5
Approach level SPF goodness of fit and parameter estimate results.

	Total Collisions	Severe Collisions	PDO collisions	Rear-End Collisions	Angle Collisions
Parameter Estimates					
Intercept	−9.12(0.635, *<0.001*)	−10.19(0.833, *<0.001*)	−9.61(0.671, *<0.001*)	−13.00(0.870, *<0.001*)	−11.29(0.953, *<0.001*)
Major ADT	0.76 (0.047, *<0.001*)	0.71 (0.061, *<0.001*)	0.79 (0.049, *<0.001*)	1.06 (0.065, *<0.001*)	0.77 (0.073, *<0.001*)
Minor ADT	0.30 (0.044, *<0.001*)	0.32 (0.056, *<0.001*)	0.30 (0.045, *<0.001*)	0.32 (0.056, *<0.001*)	0.32 (0.064, *<0.001*)
Right Turn Separation	0.22 (0.040, *<0.001*)	0.12 (0.050, *0.017*)	0.25 (0.041, *<0.001*)	0.42 (0.051, *<0.001*)	–
Approaches	–	–	–	–	0.77 (0.223, *<0.001*)
Goodness of Fit					
Dispersion parameter	0.28	0.32	0.30	0.44	0.46
Degrees of Freedom	336	336	336	336	336
Pearson X-Square	385.85	400.81	389.04	388.18	394.86
Scaled Deviance	355.66	330.25	364.96	375.29	383.56

(SE, p-value).

Table 6
Approach Level Before-and-After Evaluation Results.

	% Collision Reductions (SE)					
	ISD Approaches		Non-ISD Approaches (No Signs)		Non-ISD Approaches (Signs)	
Total Collisions	11.55[a]	(3.53)	−4.30	(6.17)	−4.18	(6.11)
Severe Collisions	−3.06	(9.12)	−33.01	(16.54)	2.10	(15.47)
PDO collisions	11.74[a]	(3.99)	−1.17	(6.73)	−8.11	(6.95)
Rear-End Collisions	13.63[a]	(4.14)	0.29	(7.34)	3.64	(6.73)
Angle Collisions	43.06[a]	(8.64)	79.84[a]	(7.45)	35.55[a]	(16.36)

[a] Significant at 95% level.

Table 7
Evaluation results for site selection criteria.

% Collision Reductions (SE)							
	Threshold	Group Size	Total Collisions	Severe Collisions	PDO Collisions	Rear-End Collisions	Angle Collisions
Collision Frequency	≤ 10	14	−10.17 (7.57)	−33.10 (20.89)	−9.42 (8.29)	−3.10 (8.39)	35.35[a] (14.62)
	(10, 15]	13	16.80[a] (5.29)	−9.00 (15.03)	14.28[a] (6.81)	24.77[a] (5.71)	49.90[a] (12.68)
	>15	15	26.39[a] (5.77)	29.06[a] (12.50)	7.34[a] (3.22)	14.76 (8.13)	47.90[a] (18.64)
Collision Rate	≤ 1.1	12	−6.33 (6.98)	−37.91 (20.88)	−2.30 (7.50)	−1.38 (7.65)	40.10[a] (14.61)
	(1.1, 1.6]	14	18.84[a] (5.09)	5.99 (12.81)	18.57[a] (5.84)	27.40[a] (5.52)	54.05[a] (11.74)
	>1.6	15	22.71[a] (6.57)	19.44 (15.10)	20.15[a] (7.74)	10.19 (9.74)	29.54 (21.64)
AADT	$\leq$25,000	18	24.74[a] (5.41)	5.07 (15.11)	26.70[a] (6.01)	34.09[a] (5.96)	41.83[a] (13.34)
	(25–30]	12	−2.10 (7.14)	−31.03 (19.24)	0.76 (7.92)	−5.73 (9.02)	54.68[a] (15.18)
	>30,000	12	10.02 (5.97)	13.53 (13.53)	5.99 (6.98)	8.62 (6.89)	37.64[a] (16.11)

[a] Significant at 95% level.

lognormal distribution. The functional form of the model is shown in Eq. (8).

$$\theta = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots + \beta_n X_n + \varepsilon \tag{8}$$

where, X_1, X_2, ..., X_n are the independent variables related to approach characteristics, i.e. the number of lanes, speed limits, average lane width, and presence of separated right turn lanes. The speed limits for the ISD sites were either 50, 60, or 70 km/h. Insignificant variables were removed in a backwards stepwise process to find the model with the best fit. The regression analysis was repeated for all the collision categories and the results are summarized in Table 8.

Three variables were significantly related to an increase in the safety effectiveness of the ISD, namely, speed limits, the number of lanes, and presence of a separated right turn lane. For total collisions, the variable parameters suggest that reductions were greater for approaches with more lanes, and for approaches with lower speed limits. Only the right turn separation variable was found to be significant for the model representing angle collisions; reductions were greater for intersections without separated right turn

Table 8
Results of regression analysis of intersection characteristics.

	Total Collisions	Severe Collisions	PDO collisions	Rear-End Collisions	Angle Collisions
Intercept	−1.98 (0.008)	−2.725 (0.030)	−1.384 (0.061)	−2.854 (0.001)	1.258 (0.0032)
Number of Lanes	−0.142 (0.008)	–	−0.135 (0.011)	−0.190 (0.003)	−0.704(<0.0001)
Speed Limit	0.041 (0.001)	0.045 (0.024)	0.031 (0.012)	0.058 (<0.0001)	–
Right Turn Separation	–	–	–	–	1.29 (0.0003)

(P-value).

Table 9
Site selection criteria.

	Speed Limit			Right Turn Lane Separation		Number of Lanes	
Threshold	50 km/hr	60 km/hr	70 km/hr	No	Yes	2 – 4	5 –7
Group Size	7	25	8	8	32	19	21
Total	2.90	20.50[a]	−12.79	14.37	11.22[a]	10.95	11.95 [a]
Severe	16.02	4.31	−29.40	25.26	−7.17	8.66	−10.10
PDO	−4.25	19.52[a]	−12.67	0.89	11.51 [a]	5.87	12.76 [a]
Rear-End	16.14	23.72[a]	−17.81	25.86[a]	12.51 [a]	8.90	15.93 [a]
Angle	27.77	46.14[a]	46.21[a]	−0.36	49.87 [a]	28.00	53.89 [a]

[a] Significant at 95% level.

lanes. The study by (De Pauw et al., 2014) also found that collision reductions were highest at sites where ISDs were installed and combined with other measures such as lowering speed limits. In order to check the correlation between the three independent variables, the SAS CORR procedure was used and the results showed that the variables were weakly correlated.

In order to further explore these trends the treatment sites were classified into groups based on three intersection characteristics found to be significant from the regression analysis. The EB analysis was repeated for these three criteria using all the previously discussed collision types. Three threshold classifications were created for the speed limit criterion and two threshold classifications were used to analyse the impact of the number of lanes and the presence of right turn separation. The results of the analysis are shown in Table 9. Sites with lower speed limits (50 km/h or 60 km/h) generally had greater reductions than sites with a speed limit of 70 km/h. Sites which did have separated right turn lanes had significant reductions in collisions, while sites without separated right turn lanes did not. The difference was greatest for angle collisions which showed a significant 50% reduction in collisions at sites with separated right turn lanes and showed a small non-significant increase at sites that do not have right turn separation. The exception was for rear-end collisions; the reductions were greater at sites that did not have right turn separation (26% vs 13%). Finally the number of lanes is also shown to impact the effectiveness of ISDs. Sites with 5–7 lanes had greater collisions reduction for almost all collision types, again the difference was greatest for angle collisions which showed a 54% decrease in collisions at sites with a higher number of lanes comparted to a decrease of 28% at sites which had 2–4 lanes.

Overall, it is clear that there can be significant collision reductions after the installation of ISDs. Additionally, the analysis revealed that certain characteristics and features can largely influence the effectiveness of ISDs. In fact, future selection of ISD sites can be refined by examine issues pertaining to historical collision frequencies or rates, lowered speed limits and specific intersection characteristics such as number of lanes and right turn separation. All of the above mentioned issues were show to impact the effectiveness of ISDs.

5. Conclusion

This study conducted a before-and-after EB evaluation of ISDs using data from the City of Edmonton. Local SPFs and YCFs for five different collision classifications were developed for use at both the intersection and approach level. Significant reductions were observed for nearly all the collision classifications at the intersection level with the exception of severe collisions. Throughout the evaluation, the collision reduction results for the severe collision classification were mainly non-significant. The collision occurrence for severe collisions was much lower than the other collision categories; this is likely the reason for the non-significant results. However significant reductions in severe collisions was observed for locations with greater than 15 yearly collisions in the before period (29%). At both the intersection level and approach level, there were significant reductions in total collisions (25% and 12%) and angle collisions (33% and 43%). In addition, significant reductions were found for rear-end collisions (11% and 14%).

The evaluation of the site selection criteria suggests that ISDs can be most successful when they are implemented at locations that meet certain criteria. From this study it was found that sites with high collision frequencies generally show greater reductions in collisions after ISDs are installed. Additionally, regression analysis suggests that ISDs installed at approaches with lower speed limits and more lanes general may be more successful at reducing collisions. Using these criteria can help in developing future ISD deployment strategies and increase the success of ISD programs.

Previous studies of RLCs and ISDs have attempted to estimate the spillover effect to surrounding intersections. A *meta*-analysis by Høye (2013) suggests that there are generally not strong spillover effects from RLCs—only a mild indication of spillover of right-angle collision reduction. Vanlaar et al. (2014) found evidence of spillover in rear-end collisions, but not significant spillover in target collisions. In this study, it was not possible to evaluate the impact of spillover effects at other intersections. This issue could be further investigated in future research although the evidence from the literatures suggests that any spillover effects would be marginal.

In summary, the primary finding in this paper can be summarized as follows:

- At the intersection level there were significant reductions in total collisions, angle collisions and rear-end collisions (25%, 33% and 11%).
- At the approach level there were significant reduction in total collision, angle collisions and rear-end collisions (12%, 43%, and 14%).
- Significant reductions in severe collisions was observed for locations with greater than 15 yearly collisions in the before period (29%).

- Small spillover effects were evident for angle collisions, but no spillover effects were observed for other collision types.
- Collision frequency and collision rate were found to be successful as site selection indicators, however AADT was not found to be a successful site selection criteria for ISD selection.
- The three intersection characteristics were found to have an impact on ISD collision reduction include: number of lanes, separated right turn lane presence, and speed limit.

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