A Before-and-After Empirical Bayes Evaluation of Automated Mobile Speed Enforcement on Urban Arterial Roads

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ABSTRACT

This study evaluates the safety effects of automated mobile enforcement on urban arterial roads. The before-and-after Empirical Bayes (EB) method was used to account for the regression-to-the-mean effects and other confounding factors. Locally developed safety performance functions and yearly calibration factors for different collision severities were obtained by using a reference group of urban arterial roads. Eight years of data was collected to perform the evaluation, including information on collision records, deployment information, traffic counts, and geometric road data. The results showed consistent reductions in different collision severities, ranging from 14% to 20%, with the highest reductions observed for severe collisions. The enforced segments were further categorized according to site selection criteria and deployment hours to examine their effects on collision reduction. The study also compared the safety effects of continuous and discontinuous enforcement strategies on different arterials, and the analysis revealed that continuous enforcement had a stronger influence on all severity/type of collisions. Moreover, the study also investigated the spillover effects on adjacent approaches, and the findings were discussed with regard to the general and specific deterrence of the enforcement.

KEYWORDS

Automated Mobile Enforcement; Before-and-After Evaluation; Empirical Bayes (EB); Yearly Calibration Factor; Continuous vs. Discontinuous Enforcement; Spillover Effect

1. INTRODUCTION

Traffic collision is a serious global issue, causing around 1.2 million deaths each year (*1*). Despite the fact that most collisions are unintended and unexpected, many of them can be prevented through changing drivers' behaviour on roads. Traffic law violation is one of the most widespread misbehaviours and is significantly associated with an increased risk of traffic collisions and injuries (*2*). In fact, a study in Norway has shown that fatalities could be reduced by 48% if 16 of the most frequent traffic law violations were eliminated (*3*). Many jurisdictions have therefore initiated several traffic enforcement programs to increase drivers' compliance to traffic laws (*4, 5, 6, 7*).

The causal link between speed and safety is well-established in the literature (*8*). The risk is greater because driving at a high speed leaves the driver with less time to react and increases the distance needed for a vehicle to come to a complete stop. It was shown in the literature that a 5% increase in mean speed may lead to approximately a 10% increase in injury collisions and a 20% increase in fatal collisions (*9*). In Canada, collision statistics suggested that 27% of fatalities and 19% of serious injuries involved speeding (*5*). Unfortunately, speed violation is a widespread phenomenon, and its danger is usually underestimated, if not altogether ignored, by the public (*6, 7, 10*). An extensive survey showed that on average 40% to 50% of drivers were driving above the speed limit (*9*). Speed enforcement is often adopted to reduce excessive speeding, and it is regarded as one of the most direct and effective methods to improve compliance (*11*).

The mechanism of speed enforcement stems from the deterrence theory, which can be further divided into general deterrence and specific deterrence (*12, 13*). General deterrence is the impact of the threat of legal punishment on the public at large, while specific deterrence is the impact of actual legal punishment on those who have been apprehended. The extent of the deterrence usually depends on the intensity of deployment, tolerance for the violation, and the influence of public campaigns along with the program. During enforcement, a speed measurement device will be used to detect speeding vehicles, and a penalty will be issued to the driver or the owner of the vehicle after validation and verification.

Generally, there are two types of speed enforcement: conventional (manned) enforcement and automated enforcement. Conventional enforcement is usually conducted by police officers with speed measurement devices. It involves an immediate and direct interaction between the enforcement officers and the violators, which enables the verification of the violator to be more objective. However, conventional enforcement is not suitable for high traffic volume sites and may cause risk to personnel during the operation. Therefore, automated enforcement was proposed as a safer and more accurate alternative to conventional enforcement (*9*). The automated mechanism of the speed measurement detector and photo camera greatly reduces labour resources. The device can be operated as long as necessary, with or without the presence of enforcement officers, and can be either fixed at certain sites or mobile by mounting it on enforcement vehicles.

Compared to fixed automated enforcement, mobile automated enforcement offers much more flexibility in its operation. Each enforcement device can be easily rotated among multiple enforcement sites at different time periods, according to needs. Consequently, the coverage of the mobile enforcement program can be much higher than fixed enforcement given the same number of devices. Another merit of mobile enforcement is its potential in covert operation. The existence of fixed cameras at specific sites is likely to become public knowledge, especially when the program continues for a long time period. Drivers were observed to slow down near the enforcement devices and then speed up to compensate for lost time (*6*). Mobile enforcement devices can be installed in unmarked vehicles and implemented at different sites, thereby increasing the unpredictability of enforcement and creating a wider range of deterrence effects. One successful example is the Random Road Watch program in Queensland, Australia (*4*). A randomized scheduling method was adopted to achieve widespread coverage for enforcement. It was reported that the enforced roads originally contained 55% of total collisions within the state, and the results of enforcement demonstrated a 31% reduction in fatal collisions.

Safety effects of automated mobile enforcement on both collision and speed have been validated by many studies (*10, 14, 15, 16, 17*). However, most of the studies adopted an interrupted time-series analysis to evaluate the system-wide effect. In the very few studies that focused on site-based effects, the results were weakened due to deficiencies in the adopted methodology, i.e., failure to account for the regression-to-the-mean effects and confounding factors, etc. (*7*). In addition, most evaluations were made shortly after the program's implementation. Some studies found that the effectiveness of the program was highest during the starting stage but diminished over time. The effectiveness of automated enforcement over a longer time of period needs to be further confirmed (*18, 19, 20*).

Given the above points, this study has three main objectives. First, this study will attempt to estimate the effectiveness of mobile automated enforcement on urban arterial roads using the before-and-after evaluation with Empirical Bayes (EB) adjustment, as outlined in the Highway Safety Manual (2*1*). Arterial roads handle the heaviest traffic volumes in cities, and as a result, a majority of collisions occur on arterial roads. Although arterial roads have always been important targets of enforcement operations, no previous studies found have explicitly evaluated the safety effects of mobile enforcement on them. This represents a critical gap in the literature that needs to be addressed. Since enforcement resources are always limited, it is important to decide how to distribute them to achieve better results. Consequently, the second objective of this study is to investigate and compare the safety effects of different enforcement strategies, by examining the changes in collision frequency for continuously enforced sites (i.e., defined here as sites that have been enforced each year during the after period) and the sites that were not. Finally, the spillover effect will be investigated by comparing enforced and unenforced arterial approaches. This was done to examine whether enforcement operations had any impact on the safety performance of adjacent approaches.

2. PREVIOUS WORK

Carnis and Blais conducted an assessment of French speed camera program (*22*). The national enforcement program started in 2003. In total, 2,756 speed cameras had been installed nation-wide in 2010, among which 933 were mobile ones. The study adopted interrupted time-series analyses using autoregressive, integrated, moving average (ARIMA) intervention time-series models. The estimates showed that the introduction of the program was associated with a significant reduction in both traffic fatalities and injuries. To further calculate the actual reduction percentage, models with and without intervention parameters were compared. A 21% reduction was found in the fatality rate per 100,000 vehicles, while the injury rate of reduction diminished from 26.2% to 0.8% as time went on.

Queensland, Australia, applied a randomized schedule method in its Random Road Watch (RRW) traffic-policing program. Instead of focusing only on high collision sites, each police station operated an individual program covering as many routes in the station's territory as possible. The time-of-day and day-of-week of the enforcement schedule at each site was generated randomly, making the operation highly unpredictable (*23*). Newstead et al. (*4*) applied a quasi-experimental design framework with a Poisson regression model to evaluate the effects of the program on different severities of collisions. Results revealed that the highest reduction was obtained in fatal collisions (31%), and the effects decreased with severity level. Although the effects remained stable for the fatal collisions, those on other severities of collisions were enhanced rather than diminished through the program. The estimated benefit cost ratio for the program reached 55:1.

Goldenbeld and Schagen conducted a study on a mobile enforcement program in one Dutch province (*10*). The study design was a before-and-after study with a comparison group. The odd ratios for both injury accidents and serious traffic casualties were calculated with a 95% confidence interval. It was found that both ratios were 0.79, indicating a 21% reduction due to the mobile enforcement program. However, the authors mentioned some limitations of the study. The numbers of roads and collisions were small for statistical purposes. More importantly, although the enforced roads were selected based on a relatively long period of data, the regression-to-the-mean effect could have still influenced the estimation results. The authors suggested that the EB method as proposed by Hauer (*24*) would be a sound method to solve the problem.

In addition, Chen et al. (*14*) investigated the safety effects of the covert mobile photo radar program in British Columbia, Canada. Monthly traffic victims and fatalities were analyzed with the interrupted time-series method. The results showed 25%, 11%, and 17% reductions in the numbers of daytime speed-related collisions, daytime traffic collision victims carried by ambulances, and daytime traffic collision fatalities. However, the evaluation focused only on the first year of the operation, and the impact may have decreased over time.

All the studies mentioned above confirmed the effects of mobile enforcement on traffic safety. However, most of the previous works on mobile enforcement used the system-wide collisions rather than road segment-based collisions. Although the system-wide evaluation can identify the general effect of mobile enforcement on safety at the municipal/national level, specific effects on individual enforced segments remain unclear. As for the site-based studies, the regression-to-the-mean effect was hard to accommodate due to the difficulties in finding a sufficient number of reference sites that have characteristics similar to the enforced sites. Additionally, change in traffic volume, trend, and confounding factors (such as reporting threshold) will also affect the quality of the evaluation results (*7*). These issues were explicitly dealt with in this study. In addition, this study also examined the issues of continuous versus discontinuous enforcement effects and spillover effects on the opposite approach segment, which are rarely discussed in previous studies.

3. DATA

This study covered the time period between January 2005 and December 2012. The enforced segment in this study refers to one approach of the roadway that faced the same direction as the enforcement operation. Yearly data on deployment, traffic counts, collisions by type/severity, and road geometric data were linked and collected from different databases from the City of Edmonton, Alberta, Canada. The types of collisions included:

- Property Damage Only (PDO) Collisions;
- Severe Collisions (sum of all the fatal and injury collisions);
- Total Collisions;
- Speed-related PDO Collisions; and
- Speed-related Collisions.

It should be noted that only mid-block collisions were considered in this study. This is due to the fact that intersection collisions have distinct characteristics and may not be directly influenced by the speed enforcement operation. A statistical summary of the evaluated segments data is shown in Table 1.

TABLE 1 Summary Statistics of the Dataset

	Average	Standard Deviation	Minimum	Maximum
Average Yearly* Deployment Hour	37.2	53.4	1.0	279.6
Segment Length (meters)	962	508	184	3233
Median (0: no, 1: yes)	0.5	0.5	0	1
Unsignalized Intersection Density (/km)	4.2	3.1	0	15.8
Average Yearly AADT	9781	5094	2079	22960
Average Yearly Severe Collision	0.6	0.7	0.0	3.1
Average Yearly PDO Collision	3.1	3.7	0.3	23.9
Average Yearly Total Collision	3.8	4.3	0.3	27.0
Average Yearly Speed-related PDO Collision	1.8	1.8	0.1	11.3
Average Yearly Speed-related Collision	2.4	2.4	0.2	14.4

* Average Yearly means the average of the yearly data during the study period

4. METHODOLOGY

4.1 Safety Performance Function

Safety performance functions (SPF) are regression models that are used to estimate the predicted average collision frequency for specific type of road segments or intersections. In this study, the generalized linear model (GLM) was adopted to examine the relationship between the number of collisions and explanatory variables. Compared with traditional linear regression, GLM is able to capture collision distribution. The negative binomial (NB) error structure was used to describe the collision distribution. Previous research has shown that the NB distribution is able to better describe the overdispersion in collision data compared to the Poisson distribution, which limits the mean to be equal to the variance (*25, 26, 27*). A standard SPF model form for road segments was selected. In the model, the predicted yearly average number of collisions is the dependent variable, while traffic volume and road geometric characteristics are the independent variables. The model form in this study is shown in Equation (1):

$$\ln(\mu) = \beta_0 + \beta_1 \ln(V) + \beta_2 \ln(L) + \beta_3 UNSD + \beta_4 Median \quad (1)$$

Where:

μ = predicted yearly average collision frequency

V = annual average daily traffic of the road segment

L = length of the road segment (km)

$UNSD$ = density of the unsignalized intersection (/km)

$Median$ = dummy variable for the presence of median

$\beta_0 - \beta_4$ = regression parameters

The goal of developing local SPFs is to obtain an average number of collisions given the traffic volume and geometric characteristics of a particular road segment. The number serves as a "baseline" in the local environment. Thus, the quality of the reference segments group is crucial to the accuracy of the prediction. A sufficient sample size is also important to strengthen the statistical power of the models. To this end, a thorough selection of reference segments was conducted within the scope of the whole city. The criteria for the selection are listed below:

- Arterial road segment;
- Similar traffic volume;
- Similar collision frequency;
- No enforcement; and
- Not adjacent to enforced segments.

In total, 266 arterial segments were selected to develop the local SPFs. The parameters were estimated in SAS through the GENMOD procedure (*28*), which uses the maximum likelihood estimation with the Newton-Raphson algorithm. The goodness of fit of the models was measured by the scaled deviance (SD) and the Pearson χ^2, which are widely used for the negative binomial distribution. Both the SD and the Pearson χ^2 are asymptotically χ^2 distributed with $n-p$ degrees of freedom for other distributions of the exponential family, where n is number of observations and p is the number of regression parameters (*29*).

4.2 Yearly Calibration Factor

The SPFs contain only traffic volume and road geometric variables and are estimated using combined data during the study period. Thus, they are not able to capture the annual fluctuation in collision frequency caused by confounding factors, such as weather conditions, roadway improvement, and general trends in traffic safety (*30*). The yearly calibration factors are calculated as the ratios between the sum of the observed number of collisions and the sum of the average number of collisions predicted by SPFs in the same year using the reference group data (Equation 2). The underlying assumption is that the impacts of the confounding factors on collision variation are similar for both the reference segments and the enforced segments. The predicted average number of collisions by the SPFs will be adjusted through multiplying the corresponding yearly calibration factor to obtain more accurate prediction.

$$C_{ij} = \frac{\sum_{Allsites} N_{ij}}{\sum_{Allsites} \mu_{ij}} \qquad (2)$$

Where:

C = yearly calibration factor

N = observed number of collisions

μ = predicted average number of collisions

i = collision type/severity

j = year

4.3 Before-and-After Evaluation with Empirical Bayes Method

The regression-to-the-mean (RTM) effect reflects the random variation of collision frequency in the absence of any external factors. In other words, the high collision frequency at one site will drop after a period of time even if no countermeasure is implemented. Since most jurisdictions are likely to prioritize high collision sites for enforcement, significant reduction obtained using the conventional evaluation techniques may be biased due to the ignorance of the RTM effect. The Empirical Bayes (EB) method proposed by Hauer (*24*) explicitly addressed this issue by incorporating collision information from reference sites into the evaluation. The EB method is also able to account for the changes in traffic volume and length of the before and after periods. The evaluation procedure is described below.

The first step is to calculate the expected number of collisions for the before period for each site. The expected number of collisions is the sum of the weighted observed number of collisions and the predicted number of collisions adjusted by the yearly calibration factor. The calculations for the expected number of collisions are shown in Equations (3) and (4). In this study, the minimum length of the before period was chosen as two years while the minimum length of the after period was chosen to be one year.

$$E_B = w \cdot \mu_B + (1-w) \cdot N_B \tag{3}$$

$$w = \frac{1}{1 + k \cdot \mu_B} \tag{4}$$

Where:

w = weight used in calculating expected number of collisions

E_B = sum of expected number of collisions for the before period

μ_B = sum of predicted number of collisions for the before period

N_B = sum of observed number of collisions for the before period

k = overdispersion parameter estimated in SPF

The second step is to calculate the expected number of collisions for the after period. A multiplier is developed to account for the differences in the period length and traffic volume between the before period and the after period. This multiplier is the ratio between the predicted collisions for the after period and the predicted collisions for the before period. The expected number of collisions for the after period can be calculated by applying this multiplier to the expected number of collisions for the before period.

The third step is to calculate the overall odds ratio of collision reduction (θ) and its standard error, which are shown in Equations (5), (6) and (7).

$$\theta = \frac{\sum_{Allsites} N_A \Big/ \sum_{Allsites} E_A}{1 + Var(\sum_{Allsites} E_A) \Big/ (\sum_{Allsites} E_A)^2} \tag{5}$$

$$Var(\sum_{Allsites} E_A) = \sum_{Allsites} [(\mu_A / \mu_B)^2 \times E_B \times (1-w)] \tag{6}$$

$$SE(\theta) = \sqrt{\frac{(\sum_{Allsites} N_A \Big/ \sum_{Allsites} E_A)^2 [\frac{1}{\sum_{Allsites} N_A} + Var(\sum_{Allsites} E_A) \Big/ (\sum_{Allsites} E_A)^2]}{[1 + Var(\sum_{Allsites} E_A) \Big/ (\sum_{Allsites} E_A)^2]}} \tag{7}$$

Where:

N_A = sum of observed number of collisions for the after period

E_A = sum of expected number of collisions for the after period

μ_A = sum of predicted number of collisions for the after period

The last step is to assess the statistical significance of the estimated collision reduction percentage, which is calculated as $100 \cdot (1-\theta)$ with a standard error of $100 \cdot SE(\theta)$. The ratio between the reduction percentage and its standard error is compared with the critical values for significance. If the value of the ratio is greater than 1.97, the collision reduction percentage is significant at the 95% confidence level. If the value of the ratio is greater than 1.65, the collision reduction percentage is significant at the 90% confidence level; otherwise, it is not significant at 90% confident level.

5. RESULTS AND DISCUSSIONS

5.1 SPFs and Yearly Calibration Factors

The local SPFs were developed using the data and methodology described above. The models' goodness of fit was measured by two statistics: scaled deviance and Pearson χ^2, which are shown in Table 2. As demonstrated in the table, all the models fit the data relatively well. The estimation results for the regression parameters are shown in Table 3. All the parameters are highly significant, except for the median parameter in the speed-related PDO collision model. The signs of the parameters are intuitive. The collision frequency increases with traffic volume, segment length, and unsignalized intersection density, while it decreases when there is a median present. All the shape parameters were highly significant, which validates the presence of overdispersion in the data. The yearly calibration factors by year and by collision severity/type are shown in Table 4.

TABLE 2 SPF Models' Goodness of Fit

	Severe Collision	PDO Collision	Total Collision	Speed-related PDO Collision	Speed-related Collision
Scaled Deviance	294.01	281.19	279.93	282.08	279.94
Pearson χ^2	269.84	286.41	288.19	294.99	289.37
Degrees of freedom	261	261	261	261	261
$\chi^2_{.05}$	299.68	299.68	299.68	299.68	299.68

TABLE 3 SPFs Estimate Results

	Severe Collision	PDO Collision	Total Collision	Speed-related PDO Collision	Speed-related Collision
Intercept	-10.25*	-5.87*	-6.00*	-6.48*	-6.73*
AADT	1.05*	0.74*	0.78*	0.75*	0.81*
Length	0.44*	0.36*	0.38*	0.40*	0.41*
UNSD	0.06*	0.07*	0.07*	0.07*	0.06*
Median	-0.28*	-0.32*	-0.31*	-0.15	-0.18**
Dispersion Parameter	0.38*	0.34*	0.34*	0.34*	0.34*

* Significant at 99% level ** Significant at 95% level

TABLE 4 Yearly Calibration Factors

Year	Severe Collision	PDO Collision	Total Collision	Speed-related PDO Collision	Speed-related Collision
2005	1.19	0.81	0.88	0.86	0.95
2006	1.43	0.95	1.03	0.99	1.11
2007	1.20	1.00	1.03	0.99	1.05
2008	0.98	1.11	1.09	1.12	1.09
2009	0.74	1.19	1.12	1.22	1.10
2010	0.80	1.10	1.05	1.11	1.03
2011	0.72	0.91	0.88	0.81	0.79
2012	0.90	0.98	0.97	0.92	0.92

5.2 Overall Before-and-After Evaluation

In total, 93 enforced arterial road segments were evaluated with the before-and-after EB method following the procedure described in the methodology section. For each site, the adjusted yearly predicted number of collisions was calculated using the corresponding traffic volume data and calibration factor of that year. Finally, the overall collision reduction percentage and its statistical test ratio by collision severity/type are shown in Table 5. The results suggest that there were significant reductions in all collision severities and types. The highest reduction occurred for severe collisions at 20.1%. The results are consistent with other evaluations of automated mobile enforcement. Newstead et al. found a 31% reduction in fatal collisions and an 11% reduction in total collisions in the Queensland Random Road Watch program (*4*)**.** A 25% reduction in daytime speed-related collisions was estimated for British Columbia mobile enforcement (*14*). The French speed camera program reduced the fatality rate per 100,000 vehicles by 21% (*22*). The results here also indicate that the enforcement had greater impacts on the severe and speed-related collisions in comparison to the others listed in Table 5.

TABLE 5 Overall Before-and-After Evaluation Results

	Severe Collision	PDO Collision	Total Collision	Speed-related PDO Collision	Speed-related Collision
Collision Reduction (%)	20.1	14.3	14.5	17.9	18.5
Statistical Test Ratio	2.3*	3.29*	3.64*	3.3*	3.91*

* Significant at 95% level

The selection of the enforced segments was mainly based on local expertise and historical data. However, jurisdictions that lack a comprehensive dataset or experiences in managing an automated mobile enforcement program may find it useful to deploy their resources using simple criteria and thresholds for enforcement. To provide insight into the effects of different site selection criteria on the effectiveness of photo radar enforcement, the 93 segments were reclassified into groups according to three basic site selection criteria that were identified previously in the literature (*31*):

- The average number of collisions per year during the before period;
- The average AADT during the before period; and
- The average collision rate during the before period (average number of collisions per million vehicle kilometers travelled per day).

For each criterion and collision severity/type, the 93 enforced segments were grouped into three categories according to a pre-specified threshold. After the reclassification, a safety evaluation was conducted within each category, and the results are shown in Table 6.

In general, more reductions were achieved for the segments that had a high number of collisions or high collision rates during the before period. For example, a 20% significant reduction is expected to be achieved if the segment has more than three speed-related collisions per year or more than one speed-related collision per million vehicle kilometers travelled per day. The evaluation results based on the AADT criterion revealed that segments with an average AADT between 7,000 and 12,000 experienced the highest reduction, ranging from 26% to 31%.

It should be noted that the magnitude of the reduction is the outcome of both the characteristics of enforced segments (i.e., based on the three site selection criteria) and the assigned enforcement resources (i.e., total and average deployment hours). Consequently, the 93 segments were regrouped by the deployment hour (both total and yearly average) to examine the effects of different deployment strategies on collision reduction. The evaluation results are shown in Table 7. It can be observed that there are significant reductions, regardless of the collision type, for the segments that had total deployment hours above 70 or average yearly deployment hours above 30. However, the average values of these segments are actually 310 for total deployment hours and 96 for the average yearly deployment hours, which are much higher than the thresholds. Nevertheless, the results do indicate that a longer deployment length can lead to greater collision reduction.

TABLE 6 Evaluation Results by Site Selection Criteria

Criterion		Collision			AADT			Collision Rate		
Severe Collision	Threshold	< 0.3	[0.3, 1)	≥ 1	< 7000	[7000, 12000)	≥ 12000	< 0.2	[0.2, 0.4)	≥ 0.4
	Reduction (%)	15.1	27.1**	19.1	12.7	26.2**	19.2	14.1	25	22.4**
	Group Size	30	36	27	31	33	29	43	23	27
	Average Reduction [a]	0.11	0.27	0.52	0.08	0.35	0.44	0.13	0.33	0.51
	Average Total Hours [b]	85.6	151.4	98.3	44.9	111.4	193.3	149.9	82	86.7
	Average Yearly Hours [c]	26.5	46.6	36.4	14.4	36.3	62.4	43.1	28.8	34.8
PDO Collision	Threshold	< 1.5	[1.5, 3)	≥ 3	< 7000	[7000, 12000)	≥ 12000	< 0.6	[0.6, 1.1)	≥ 1.1
	Reduction (%)	8.3	13.6	16.6*	16.7**	27.4*	5.5	-3.5	20.5*	17.4*
	Group Size	31	34	28	31	33	29	29	31	33
	Average Reduction	0.32	0.84	2.72	0.74	2.12	0.74	-0.21	1.37	2.36
	Average Total Hours	130.2	96.7	119.6	44.9	111.4	193.3	165.9	97.2	86.3
	Average Yearly Hours	33.4	34.6	44.4	14.4	36.3	62.4	45.5	33.8	32.9
Total Collision	Threshold	< 1.5	[1.5, 3.5)	≥ 3.5	< 7000	[7000, 12000)	≥ 12000	< 0.8	[0.8, 1.5)	≥ 1.5
	Reduction (%)	2.9	7.1	19.4*	16.3**	26.5*	6.4	-1.8	22.9*	17.4*
	Group Size	28	32	33	31	33	29	33	29	31
	Average Reduction	0.1	0.4	3.63	0.85	2.42	1.01	-0.14	1.7	2.92
	Average Total Hours	148.8	86	113.8	44.9	111.4	193.3	193.4	52.2	89.5
	Average Yearly Hours	39.5	31.4	40.7	14.4	36.3	62.4	55	20.4	33.9
Speed-related PDO Collision	Threshold	< 1	[1, 2)	≥ 2	< 7000	[7000, 12000)	≥ 12000	< 0.4	[0.4, 0.8)	≥ 0.8
	Reduction (%)	28.8*	6.1	20.2*	24.7*	30.5*	7.6	6.9	19.4**	22.7*
	Test Ratio	2.5	0.6	2.8	2.2	3.5	0.9	0.5	1.9	3.1
	Average Reduction	0.74	0.21	1.78	0.69	1.32	0.56	0.22	0.67	1.68
	Average Total Hours	127.2	102.3	114.4	44.9	111.4	193.3	160.6	98.5	87.5
	Average Yearly Hours	35.1	34.7	42.3	14.4	36.3	62.4	42.4	37.1	32.3
Speed-related Collision	Threshold	< 1.3	[1.3, 2.8)	≥ 2.8	< 7000	[7000, 12000)	≥ 12000	< 0.5	[0.5, 1)	≥ 1
	Reduction (%)	16.7	13.5	21.5*	22.6*	30.1*	9.5	4.5	23.1*	22*
	Group Size	33	31	29	31	33	29	28	31	34
	Average Reduction	0.51	0.62	2.5	0.8	1.73	0.91	0.17	1.07	2.07
	Average Total Hours	124	125.3	92.9	44.9	111.4	193.3	186.4	84.2	83.7
	Average Yearly Hours	33.3	43.6	34.6	14.4	36.3	62.4	50	31.6	31.6

* Significant at 95% level
** Significant at 90% level
[a] Average reduction per site
[b] Average total deployment hours per site
[c] Average yearly deployment hours per site (total deployment hours divided by the number of enforced years)

TABLE 7 Evaluation Results by Deployment Hours

	Criterion	Total Deployment Hours			Average Yearly Deployment Hours		
	Threshold	< 15	[15, 70)	≥ 70	< 9	[9, 30)	≥ 30
Severe Collision	Reduction (%)	6.2	22.9	27.3*	17.2	11.2	29.1*
	Group Size	31	31	31	33	31	29
	Average Reduction [a]	0.06	0.27	0.54	0.18	0.14	0.57
	Average Collision [b]	0.7	0.8	0.8	0.6	0.9	0.9
	Average AADT [c]	8599	9388	11597	8335	9618	11858
	Average Collision Rate [d]	0.3	0.3	0.2	0.2	0.3	0.2
PDO Collision	Reduction (%)	14.4**	6.8	18.5*	14.9**	10	16.8*
	Group Size	31	31	31	33	31	29
	Average Reduction	1.04	0.43	2.23	1.04	0.67	2.04
	Average Collision	3.2	3.2	3.4	2.6	3.1	4.1
	Average AADT	8599	9388	11597	8335	9618	11858
	Average Collision Rate	1.4	1	1.1	1.1	1.2	1.2
Total Collision	Reduction (%)	13**	8.5	18.9*	13.8**	9.6	18.3*
	Group Size	31	31	31	33	31	29
	Average Reduction	1.09	0.64	2.64	1.1	0.77	2.59
	Average Collision	3.9	4	4.1	3.2	4	5
	Average AADT	8599	9388	11597	8335	9618	11858
	Average Collision Rate	1.7	1.3	1.3	1.3	1.5	1.4
Speed-related PDO Collision	Reduction (%)	10.7	15.3	23.7*	10.7	20.6*	21.4*
	Group Size	31	31	31	33	31	29
	Average Reduction	0.37	0.57	1.67	0.38	0.85	1.45
	Average Collision	1.8	1.9	2	1.5	2	2.3
	Average AADT	8599	9388	11597	8335	9618	11858
	Average Collision Rate	0.7	0.6	0.7	0.6	0.7	0.7
Speed-related Collision	Reduction (%)	11.7	15.6**	24.1*	11.6	18.1*	23.4*
	Group Size	31	31	31	33	31	29
	Average Reduction	0.56	0.76	2.17	0.54	0.98	2.07
	Average Collision	2.5	2.7	2.8	2.1	2.9	3.2
	Average AADT	8599	9388	11597	8335	9618	11858
	Average Collision Rate	1	0.9	0.9	0.9	1.1	0.9

* Significant at 95% level
** Significant at 90% level
[a] Average reduction per site
[b] Average yearly collisions during the before period per site
[c] Average AADT during the before period per site
[d] Average collision rate during the before period per site

5.3 Continuous versus Discontinuous Enforcement Evaluation

Among all the enforced segments, some were enforced each year during the after period while others were not due to limited enforcement resources. In this section, the safety effects on the continuously enforced segments were compared with those on discontinuous enforced segments using the same methodology described in the previous section. The purpose is to examine whether continuous enforcement was more effective in reducing collisions. Before making the comparison, it is critical to control for both collision characteristics and deployment length, since they are likely to influence the collision reductions. As shown in Table 8, two groups were selected to ensure that both had similar collision data, traffic volume, and deployment length. The evaluation results are provided in Table 9. It can be observed that the continuously enforced segments had larger reductions for all severities/types of collisions compared to the segments that were discontinuously enforced. The implication of the results is that continuous enforcement is a preferred strategy leading to greater collision reduction than discontinuous enforcement.

TABLE 8 Continuous versus Discontinuous Segment Information

	Group Size	Collision [a]	AADT [a]	Collision Rate [a]	Deployment Hours [b]
Continuous	23	3.2	9272	1.4	55.4
Discontinuous	23	3.1	8683	1.2	58.5

[a] Average value per site during the before period
[b] Average value per site during the after period

TABLE 9 Continuous versus Discontinuous Enforcement Evaluation Results

	Severe Collision	PDO Collision	Total Collision	Speed-related PDO Collision	Speed-related Collision
Continuous					
Collision Reduction (%)	32.1	28.7	27.7	27.3	26.7
Statistical Test Ratio	1.74**	3.22*	3.35*	2.38*	2.64*
Discontinuous					
Collision Reduction (%)	17.9	8.5	8.6	15.0	13.4
Statistical Test Ratio	1.01	0.91	0.99	1.37	1.36

* Significant at 95% level ** Significant at 90% level

5.4 Spillover Effect on the Other Approach

The spillover effect refers to the phenomenon of nearby enforcement activities influencing collisions on unenforced segments. As enforcement activities were conducted only on one approach (direction) of the road, it is meaningful to examine whether there is a spillover effect on the other approach. Thus, 39 enforced segments that did not have enforcement on their adjacent approaches were selected from the original 93 segments. The enforced group and the unenforced group were evaluated separately; the results are shown in Table 10. The results reveal that for the enforced segments, only severe and speed-related collisions were significantly reduced, while for the unenforced segments, only the PDO collisions, total collisions, and speed-related PDO collisions were significantly reduced. One possible explanation of this might be the different effects of general and specific deterrence. Although the enforcement operations were planned to be covert, some drivers were able to recognize enforcement vehicles due to the length of time the program had been operational in Edmonton. In fact, it was easier for drivers on the adjacent approach to observe the enforcement vehicle and therefore slow down, resulting in reduced PDO and total collisions. Severe and speed-related collisions were reduced because of the specific deterrence to the aggressive violators that refuse to slow down until punished. Once again, the results confirm that enforcement is capable of improving safety.

TABLE 10 Spillover Effect Evaluation Results

	Severe Collision	PDO Collision	Total Collision	Speed-related PDO Collision	Speed-related Collision
Enforced					
Collision Reduction (%)	26.1	1.8	4.5	9.2	14
Statistical Test Ratio	2.17*	0.27	0.75	1.1	1.98*
Unenforced					
Collision Reduction (%)	2.5	14.6	14.1	15.4	11.1
Statistical Test Ratio	0.16	2.02*	2.15*	1.73**	1.38

* Significant at 95% level ** Significant at 90% level

6. CONCLUSIONS AND FUTURE RESEARCH

This study conducted a before-and-after EB evaluation of automated mobile speed enforcement on urban arterial roads. Local SPFs and yearly calibration factors for different collision types and severities were developed to increase the accuracy of the evaluation results. Significant reductions were found for all collision types with the highest percentage for severe collisions, followed by speed-related collisions. The reduction ranged from 14% to 20%, which is consistent with previous research findings. This confirmed the effectiveness of mobile enforcement on improving road safety. The evaluation based on site selection criteria and deployment hours suggested that, in general, segments with a high collision number/rate and longer deployment length achieved greater reduction. The comparison between the continuous and discontinuous enforced arterial roads revealed that the former experienced larger reduction in all types of collisions. Finally, the spillover effect was validated by comparing the safety effects on enforced and unenforced segments. The findings from this study have verified the effectiveness of mobile enforcement on arterial roads. It is worth examining its effects on other road types, such as collector roads and local roads. Further research may also focus on quantifying the relationship between enforcement resources and their efficiency in improving safety effects. The results will shed light on how to improve the efficiency of the enforcement program.

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