AN OBJECTIVE WARRANT SYSTEM FOR RED LIGHT CAMERAS

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Abstract

Photo-enforced traffic signals, or red light cameras (RLCs), have been shown to be an effective countermeasure to address red light running (RLR). Unfortunately, RLCs are often installed at specific intersections in reaction to public/political pressure or based on subjective recommendations from traffic engineers or enforcement officers. There is no existing analytical methodology that can objectively determine where RLCs would prove to be most effective.

The predominant goal of this research was to develop a robust methodology that allows road authorities to make objective decisions about the installation of RLCs. To develop an objective warrant system, this research evaluated the strength of relationships between the characteristics of local intersections and the frequency of RLR. There were four main areas of focus involved in this research: collision data analyses of study intersections, RLR field observations, development of a forecasting model, and establishing an RLC warrant system that considers the cost-effectiveness of the treatment.

A worksheet-based warrant system was developed to provide an efficient methodology that determines if an intersection is an appropriate candidate for RLCs. The resulting worksheet combines the predictive model that forecasts the proportion of RLR incidence, collision modification estimates associated with installing RLCs, and an economic feasibility evaluation. A threshold value for the warrant system was determined to represent the minimum number of red light violations that must occur each year to warrant RLCs based on cost-recovery.

Résumé

Les caméras à feux rouges se sont révélées être une contre-mesure efficace pour lutter contre les feux rouges. Des caméras à feux rouges sont souvent installées à des intersections spécifiques en réponse à des pressions publiques / politiques ou sur la base de recommandations subjectives d'ingénieurs de la circulation ou d'agents de l'autorité. Aucune méthode analytique existante ne permet de déterminer objectivement où les caméras à lumière rouge se révéleraient les plus efficaces.

L'objectif principal de cette recherche était de développer une méthodologie robuste permettant aux autorités routières de prendre des décisions objectives concernant l'installation de caméras red-light. Pour développer un système de mandat objectif, cette recherche a évalué la force des relations entre les intersections locales caractéristiques et la fréquence de fonctionnement des feux rouges. Les travaux de recherche ont porté sur quatre domaines principaux: l'analyse des données de collision des intersections de l'étude, l'observation sur le terrain d'un feu rouge, la mise au point d'un modèle de prévision et la mise en place d'un système de garantie de caméra rouge qui prend en compte le rapport coût-efficacité du traitement.

Un système de mandat basé sur des feuilles de travail a été développé pour fournir une méthodologie efficace qui détermine si une intersection est un candidat approprié pour les caméras red-light. La feuille de calcul résultante combine le modèle prédictif qui prévoit la proportion d'incidence du feu rouge, les estimations de la modification de la collision associées à l'installation de caméras à feu rouge et une évaluation de la faisabilité économique. Il a été déterminé qu'une valeur seuil pour le système de mandat représentait le nombre minimal d'infractions au feu rouge qui doivent être commises chaque année pour justifier le recours à des appareils photo au feu rouge sur la base du recouvrement des coûts.

1. INTRODUCTION

Drivers that disregard red lights at signal-controlled intersections are more likely to result in right-angle collisions than any other configuration. Right-angle collisions can be the most devastating configuration for occupants due to the high momentum transfer caused by high vehicle speeds and the limited protection afforded by seatbelts and airbags during side impacts. Photo-enforced traffic signals have the potential to decrease red light running (RLR) and as a result reduce right-angle collisions.

Automated traffic ticketing is against the regulations outlined in the Motor Vehicle Act of New Brunswick. The Act requires traffic violation tickets to be issued in person by an officer of the peace, unlike most other provinces. Recently the cities of Fredericton and Moncton have expressed concerns regarding the legislation and are seeking an amendment to the Motor Vehicle Act.

There is no existing analytical methodology that permits an objective determination of where RLCs should be installed. Unfortunately, it has become common to install RLCs at intersections in reaction to public/political pressure or based on the subjective recommendations from traffic engineers or enforcement officers. In the absence of an established warrant system, any recommendations are made without the benefit of thorough analyses.

The overarching goal of this research was to develop a concise and objective analytical methodology to determine if an intersection is an appropriate candidate for RLCs. This research evaluated the strength of relationships between the characteristics of local intersections and proportion of vehicles that run a red light (dependent variable). There were four main areas of focus involved in this research: collision data analyses of study intersections, RLR field observations, development of a forecasting model, and establishing an RLC warrant system that considers the cost-effectiveness of the treatment. Jurisdictional adoption of the proposed warrant system will result in a more consistent practice and overall safety improvement.

2. STUDY INTERSECTIONS

The study locations were chosen to be a representative sample of urban signalized intersections in New Brunswick. Due to data availability and time restraints, 36 study intersections were selected exclusively from Fredericton and Moncton in consultation with each city's Traffic Engineer. It was essential to incorporate a variety of local characteristics in order to produce an accurate sample of intersections. During this preliminary stage the attributes considered were data obtainability, dispersion, geometry, and traffic volumes. Data obtainability refers to the ability to acquire pre-existing information regarding each intersection. In other words, an intersection would not be included in the sample if no information regarding the collision history of the location was available. The dispersion characteristic refers to the location of the intersection within each city, which was considered to avoid clustered samples of intersections. The geometry was considered to assure that the sample included both three and four-leg configurations and intersections with exclusive left and right turn lanes. To ensure that the sample incorporated intersections with varying levels of usage, the total traffic volumes were also considered. In an effort to avoid generating a bias warrant system, the study locations were not selected on the basis of any preconceived assumption that they might have a potential for unusually high or low rates of RLR.

1.2 Collision data analyses

Collision analyses were conducted to assess the current performance of each intersection. Observed collisions are crashes that occurred at an intersection that were documented by police agencies. The documented collisions were described by the location, date, configuration, and severity of each crash. For the purposes of this study, no observed collisions prior to 2010 were taken into consideration to avoid analyzing crashes that may have occurred before significant changes were made to an intersection. This was an attempt to better reflect the more recent operating conditions of each intersection. Expected collisions were calculated using safety performance functions (SPFs), described in the Highway Safety Manual, to reflect the expected (rather than observed) operations of each intersection [1]. The SPFs evaluate intersection by the total number crashes only (i.e. collisions were not evaluated on the basis of severity or crash configuration). The predicted numbers of annual collisions were then calibrated to better reflect local conditions. A calibration factor was determined by the quotient of the total number of observed and expected collisions from the study locations. The sum of the observed and expected annual were 225 and 125, respectively, which resulted in a calibration factor of 1.79. The anticipated collisions at each intersection were then adjusted by the calibration factor to determine a more accurate number of expected collisions. Subsequently, the potential for improvement (PFI) was calculated for each location. The PFI measures the performance of an intersection by evaluating the difference between annually observed and predicted collisions. A positive PFI indicates that an intersection is underperforming and may require upgrades such as geometry, signal phasing, signing, pavement markings, etc. Conversely, a negative PFI suggests that an intersection is performing better than expected. A summary of the collision data analyses, including the observed and expected annual collisions and the PFI, is summarized in Table 1.

1.3 Red light running study

Distributing citations for red light violations through automated technology is prohibited in New Brunswick, therefore, only a fraction of violations are documented so there is no way to know how many occur in total. An RLR field study was conducted to determine the frequency of red light

Table 1 – Summary of Collision Data Analyses

Intersection	Observed Annual Collisions	Expected Annual Collisions	Potential for Improvement (PFI)
Morton/McLaughlin	18.00	7.51	10.49
Main/Wheeler	17.00	8.27	8.73
Berry Mills/Edinburgh	10.00	5.56	4.44
Regent/Priestman	10.75	7.00	3.75
Regent/Brunswick	9.57	6.39	3.18
Vaughan Harvey/Main	9.00	6.84	2.16
Mountain/High	8.00	5.90	2.10
Regent/Prospect	11.00	9.50	1.50
Hanwell/Bishop	9.17	7.83	1.34
Regent/King's College	4.40	3.08	1.32
Main/King	14.00	12.69	1.31
John/High	3.00	2.15	0.85
St. George/Milner	5.00	4.15	0.85
Smythe/Woodstock	8.00	7.30	0.70
Assomption/Westmorland	4.00	3.60	0.40
Dundonald/York	4.29	4.63	-0.35
Smythe/Dundonald	4.71	5.22	-0.50
Route 8/Greenwood	2.20	2.77	-0.57
Regent/Arnold	6.25	6.83	-0.58
Mountain/Mapleton	6.00	6.67	-0.67
Prospect/Smythe	7.50	8.19	-0.69
Mapleton/Kendra	3.00	4.26	-1.26
Elmwood/Morton	5.00	6.30	-1.30
Regent/Beaverbrook	5.00	6.47	-1.47
Mountain/Botsford	2.00	3.55	-1.55
Main/Botsford	1.00	2.96	-1.96
Main/Brookside	2.40	4.51	-2.11
Vaughan Harvey/Millennium	3.00	5.34	-2.34
Mountain/Birchmount	4.00	6.35	-2.35
Main/Wallace	2.00	4.49	-2.49
Regent/King	4.60	7.47	-2.87
Union/Cliffe	2.25	5.34	-3.09
Mountain/Hildegard	8.00	11.52	-3.52
Lewisville/Elmwood	4.00	7.87	-3.87
Mountain/Vaughan Harvey	4.00	8.45	-4.45
Vaughan Harvey/Assomption	3.00	8.14	-5.14

violations as a result. Prior to this study, the City of Moncton, unlike the City of Fredericton, had previously conducted RLR studies at select local intersections. The results of the RLR study were provided and the procedure was then replicated to in Fredericton to complete a dataset. The frequency of RLR was determined by temporarily installing Miovision cameras at each location. The period of data collection varied for each location, however, the site was always monitored for two hours between 8:00 a.m. and 4:00 p.m., from Monday to Friday. The camera was installed to record two-hour periods, which were later inflated to reflect 24-hour totals. During each two-hour recording period, every vehicle that entered the intersection after the red signal phase began was recorded manually. For each observed violation, the direction of travel and the turning movement were documented. All of the study intersections currently permit right turns during red signal phases and were, therefore, not considered a violation and were not documented.

Upon completion of the violation surveillance, the video recordings were viewed to determine the traffic volumes during two-hour period. Unique growth factors for each maneuver were determined based on full 24-hour counts and then applied to the number of recorded violations from the observation period to produce an estimated 24-hour value for each maneuver. The total number of daily red lights run was then determined by the sum of all the maneuvers at each intersection.

The frequency of RLR was manipulated to reflect the proportion of vehicles that run a red light every day, based on the average annual daily traffic volume (AADT) at each intersection. The percent of vehicles that run a red light every day (RLR/AADT) represents the dependent variable of interest in this study. The RLR study and RLR/AADT results are summarized in Table 2.

3. RED LIGHT RUNNING PREDICTION MODEL

Given that it is difficult and costly to observe RLR frequencies, a model was developed to predict the proportion of vehicles that would be expected to run a red light on a daily basis. The model was generated by identifying and classifying possible explanatory variables, removing threats of multicollinearity, selecting the most appropriate regression model, and measuring the goodness-of-fit. The number of potential explanatory variables is nearly limitless, however, for this study, a total of 23 independent variables were collected/computed for consideration in the predictive model. The prospective variables were selected based on obtainability and their perceived potential to influence RLR frequencies. The potential predictive variables and respective classifications are outlined in Table 3.

Prior to developing the predictive model, all indications of multicollinearity were removed. Multicollinearity, or the co-dependence of variables, is a phenomenon in which two or more explanatory variables in a multiple regression model have a strong relationship [2]. To remove the threat of co-dependence, a correlation matrix was established using the list of potential explanatory variables. The correlation matrix was comprised of correlation coefficients that measured the strength of the relationship between two independent variables. If the correlation matrix demonstrated a strong relationship between two variables, they were examined in more detail. The variable with the least significance to the study was removed from the list of prospective variables. A correlation coefficient of 0.8 or greater indicated a strong relationship between variables, although any coefficient between 0.5 and 0.8 was also evaluated in more detail to avoid co-dependence between variables [3]. Other indications of multicollinearity were examined through the variance inflation factor (VIF). A VIF was determined for each parameter estimate to represent what percentage of the variance is inflated. The higher the value of VIF, the less reliable the results of the regression are. The exact value that the VIF must be to cause disruptions in the model is heavily debated upon, however, a reasonable limitation is 10. All explanatory variables associated with a VIF of 10 or more were removed from the list of potential predictor variables [2]. Upon completion of the multicollinearity analysis, the following variables remained in the list potential independent variables:

- Major Street Traffic Volume
- Minor Street Traffic Volume
- Pedestrian Volume
- Cycle Length
- Intersection Geometry
- Approaches with Left Turn Lanes
- Approaches with Right Turn Lanes
- PFI
- Right-Angle Collisions
- Head on Collisions
- Fatal Collisions
- Injury Collisions

Table 2 –Frequency and Percentage of Red Light Running

Intersection	Daily Frequency of Red Light Running	Percent of Vehicles that Run a Red Light
Assomption/Westmorland	212	1.43
Berry Mills/Edinburgh	439	1.33
Dundonald/York	381	1.55
Elmwood/Morton	325	1.00
Hanwell/Bishop	182	0.54
John/High	176	1.77
Lewisville/Elmwood	320	1.21
Main/Botsford	323	2.60
Main/Brookside	131	0.57
Main/King	279	0.70
Main/Wallace	85	0.42
Main/Wheeler	312	0.73
Mapleton/Kendra	182	0.96
Morton/McLaughlin	405	1.27
Mountain/Botsford	246	1.03
Mountain/Brichmount	187	0.82
Mountain/High	593	3.53
Mountain/Hildegard	314	0.86
Mountain/Mapleton	157	0.53
Mountain/Vaughan Harvey	213	0.64
Prospect/Smythe	283	0.70
Regent/Arnold	203	0.59
Regent/Beaverbrook	170	0.58
Regent/Brunswick	374	1.94
Regent/King	196	1.01
Regent/King’s College	90	0.69
Regent/Priestman	159	0.51
Regent/Prospect	311	0.72
Route 8/Greenwood	109	0.56
Smythe/Dundonald	141	0.37
Smythe/Woodstock	199	0.75
St. George/Milner	182	1.08
Union/Cliffe	116	0.43
Vaughan Harvey/Assomption	220	0.55
Vaughan Harvey/Main	83	0.25
Vaughan Harvey/Millennium	196	0.76

Table 3 - List of Potential Explanatory Variables

<table>
<tr><th></th><th>Variable</th><th>Category</th></tr>
<tr><td>Dependent</td><td>RLR/AADT</td><td>Continuous</td></tr>
<tr><td rowspan="33">Independent</td><td>Major Street Traffic Volume</td><td>Discrete</td></tr>
<tr><td>Minor Street Traffic Volume</td><td>Discrete</td></tr>
<tr><td>Major Street Split</td><td>Continuous</td></tr>
<tr><td>AADT Ratio ($AADT_{minor}/AADT_{major}$)</td><td>Continuous</td></tr>
<tr><td>Pedestrian Volume</td><td>Discrete</td></tr>
<tr><td>Volume-to-Capacity Ratio</td><td>Continuous</td></tr>
<tr><td>Cycle Length</td><td>Continuous</td></tr>
<tr><td>Vehicle Approach Speed</td><td>Continuous</td></tr>
<tr><td rowspan="3">Signal Control Type</td><td>Pre-Timed</td></tr>
<tr><td>Semi-Actuated</td></tr>
<tr><td>Fully Actuated</td></tr>
<tr><td rowspan="2">Coordination</td><td>Coordinated</td></tr>
<tr><td>Uncoordinated</td></tr>
<tr><td rowspan="5">Approaches with Left Turn Lanes</td><td>0</td></tr>
<tr><td>1</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td></tr>
<tr><td rowspan="5">Approaches with Right Turn Lanes</td><td>0</td></tr>
<tr><td>1</td></tr>
<tr><td>2</td></tr>
<tr><td>3</td></tr>
<tr><td>4</td></tr>
<tr><td rowspan="2">Intersection Geometry</td><td>3-Leg</td></tr>
<tr><td>4-Leg</td></tr>
<tr><td>Observed Collisions</td><td>Discrete</td></tr>
<tr><td>Expected Collisions</td><td>Discrete</td></tr>
<tr><td>Potential for Improvement</td><td>Continuous</td></tr>
<tr><td>Right-Angle Collisions</td><td>Discrete</td></tr>
<tr><td>Rear End Collisions</td><td>Discrete</td></tr>
<tr><td>Head-On Collisions</td><td>Discrete</td></tr>
<tr><td>Unknown/Other Configuration</td><td>Discrete</td></tr>
<tr><td>Fatal Collisions</td><td>Discrete</td></tr>
<tr><td></td><td>Injury Collisions</td><td>Discrete</td></tr>
<tr><td></td><td>Property Damage Collisions</td><td>Discrete</td></tr>
</table>

The remaining independent variables were modeled using Statistical Analysis Software (SAS). The dependent variable, RLR/AADT, was classified as continuous, therefore, generalized linear regression was used to develop the predictive model. Generalized linear models (GLMs) are an extension of traditional linear models, except GLMs allow the mean of a population to depend on a linear predictor through a nonlinear link function. GLMs also allows the probability distribution to be defined as any affiliate of the exponential family of distributions. The dataset was modelled with a normal probability distribution and log link functions, which was an iterative process.

The model was adjusted after each trial to only include independent variables that were statistically significant according to corresponding coefficient p-values. Explanatory variables that produced p-values less than 0.1 were considered to have a statistically significant relationship with the dependent variable at a 90% confidence level. Variables that met this restriction were included in the final model, whereas, variables that were associated with p-values greater than 0.1 were removed from the model. The SAS output from the final, most significant regression model is outlined in Table 4.

Once the model contained only variables that were statistically related to RLR, the model was then analyzed using goodness-of-fit. The observed and predicted RRL/AADT were plotted to assess the goodness-of-fit of the model, as shown in Figure 1. The goodness-of-fit was measured by applying a line of best fit to examine the slope. If the slope of the line of best fit approaches one and the intercept approaches zero, the model created in this study would represent a robust predictive model. The goodness-of-fit was also analyzed using the coefficient of determination (R^2). R^2 measures how much variance there is in the dependent variable that is predicted by the explanatory variables in the model. An R^2 value that approaches one would suggest a lower variation between the observed and forecasted values. In a rigorous model the data points on the graph would be near the line of best fit.

Table 4 - SAS Regression Model Output

Analysis of Maximum Likelihood Parameter Estimates					
Parameter	**Coefficient**	**Standard Error**	**Wald 95% Confidence Limits**		**p-Value**
Intercept	2.3624	0.2864	1.8011	2.9237	<.0001
Major Street Traffic Volume	-0.0001	0.0000	-0.0001	0.0000	<.0001
Cycle Length	-0.0094	0.0031	-0.0155	-0.0033	0.0024
Intersection Geometry	-0.4901	0.1545	-0.7930	-0.1873	0.0015
Approaches with Left Turn Lanes	-0.2615	0.0487	-0.3569	-0.1660	<.0001
Approaches with Right Turn Lanes	0.0961	0.0477	0.0026	0.1896	0.0439
Annual Right-Angle Collisions	0.1298	0.0180	0.0944	0.1651	<.0001
Scale	0.2741	0.0323	0.2176	0.3453	

The observed slope of the final model was 1.28 with an intercept of 0.30. The regression statistics were evaluated to determine if the slope and the intercept were statistically significant from one and zero, respectively. As shown in Table 5, the slope is marginally greater than one at the 95% confidence limit but is not significantly greater than one at the 99% confidence limit. The intercept is greater than zero at the 95% confidence limit and is slightly larger than zero at the 99% confidence limit. The resulting R^2 value was 0.78, which indicates that the predictive model explains 78% of the variability in the dependent variable are explained by the independent variables.

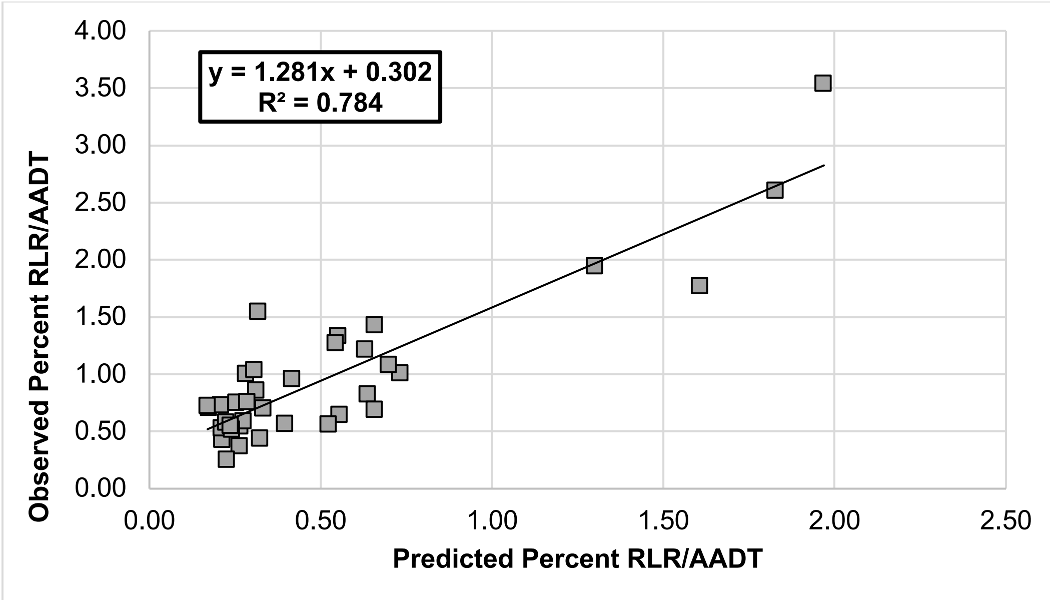

Figure 1 - Goodness-of-Fit of Final Model

Table 5 - Summary of Statistical Analysis for Goodness-of-Fit

Regression Statistics					
Multiple R	0.885				
R Square	0.784				
Adjusted R Square	0.777				
Standard Error	0.310				
Observations	36				
ANOVA					
	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	11.835	11.836	123.123	7.62E-13
Residual	34	3.2684	0.096		
Total	35	15.104			
	Coefficients	*Standard Error*	*t Stat*	*P-value*	
Intercept	0.302	0.080	3.797	0.001	
X Variable 1	1.281	0.115	11.096	0.000	
	Lower 95%	*Upper 95%*	*Lower 99.0%*	*Upper 99.0%*	
Intercept	0.140	0.463	0.085	0.519	
X Variable 1	1.047	1.516	0.966	1.596	

The dependent variable can be determined using the predictive model shown in Equation 1, which was established based on the final SAS output. Using Equation 2, the percentage of RLR can be converted to the yearly frequency of red light violations.

$$y = e^{2.3624 - 0.0001x_1 - 0.2615x_2 + 0.0961x_3 + 0.1298x_4 - 0.0094x_5 - 0.4901x_6} \quad [1]$$

Where:

- y is the predicted percentage of vehicles that will run a red light (%)
- x_1 is average observed traffic volume on the major street
- x_2 is the number of approaches that have an exclusive left turn lane (0, 1, 2, 3 or 4)
- x_3 is the number of approaches that have an exclusive right turn lane (0, 1, 2, 3 or 4)
- x_4 is the number of annually observed right-angle collisions
- x_5 is the total amount of time for the signal to complete one cycle of sequenced signal indicators (seconds)
- x_6 is 1 for a 4-leg signalized intersection or 0 for a 3-leg signalized intersection

$$Predicted\ RLR/Yr_i = \frac{y_i}{100} * AADT_i * 365\ days/yr \quad [2]$$

Where:

- $Predicted\ RLR/Yr_i$ is number of forecasted annual red light violations at intersection i
- y_i is the predicted proportion of vehicles that will run a red light daily (%) at intersection i
- $AADT_i$ is total daily traffic volume at intersection i

4. RED LIGHT RUNNING WARRANT SYSTEM

A worksheet-based warrant system was developed to provide a more efficient method for jurisdictions to determine if RLCs are warranted at a signalized intersection. The warrant system was framed from an economic analysis of prevented collisions attributed to RLCs.

The City of Fredericton estimates that an intersection safety device (ISD) costs approximately $65,000 and the associated installation costs are approximately $37,500 (2019 Canadian dollars). By taking the product of the total market value of the asset ($102,500) and the interest rate (2%) the annual maintenance costs were estimated to be $2,050 per year.

The total operating cost over the 20-year lifespan of the asset was determined by taking the sum of the expected annual maintenance costs for each year (Equation 3). The total operating costs were calculated using varying rates of return in order to frame a sensitivity analysis of the asset. Using market rates of return of 3%, 6.5% and 10%, the total operating costs were determined to be $30,500, $22,500 and $17,500, respectively. With respect to the varying operating costs, the present value of RLCs was determined to be $133,000, $125,000 and $120,000. These results are summarized in Table 6.

$$OC = \sum_{n=1}^{L} \frac{M}{(1+r)^n} \quad [3]$$

Where:

- OC is the total operating costs over lifespan
- L is the lifespan of the asset (20 years)
- M is the annual expenditures ($2050/year)
- r is the rate of return (r = 3%, 6.5%, and 10%)
- n is the age of the asset (1-20 years)

Table 6 - Red Light Camera Costs

Cost Description	Rate of Return (*r*)		
	3%	**6.5%**	**10%**
Intersection Safety Device	65,000	65,000	65,000
Construction/Installation	37,500	37,500	37,500
Operating Costs	**30,500**	**22,500**	**17,500**
Present Value	**133,000**	**125,000**	**120,000**

The average cost of an urban collision was determined using known proportions of observed collision severities and their associated costs. Of the observed urban collisions in New Brunswick, 65% result in property damage, 34.5% result in an injury and 0.5% result in a fatality [4]. The average cost of a collision resulting in a fatality, an injury (minor or major) or property damage is $5.5 million, $150,000, and $15,000, respectively, in 2015 Canadian dollars [5]. The average cost of an urban collision was determined to be approximately $96,500 based on a weighted average of the crash costs. A summary of the average collision cost can be found in Table 7. Based on the present value of RLCs and the average collision cost, a threshold was determined that defines how many collisions must be prevented by the countermeasure over the lifespan in order to be economically feasible. A minimum collision reduction over the lifespan of the asset was determined for each of the three predetermined PV possibilities. If the rate of return is 3%, the treatment must prevent a total of 1.38 collisions over 20 years (or 0.069 collisions annually). If the rate of return is 6.5%, the treatment must prevent a total of 1.30 collisions over 20 years (or 0.065 collisions annually). If the rate of return is 10%, the treatment must prevent a total of 1.25 collisions over 20 years (or 0.062 collisions annually). These results are summarized in Table 8.

Table 7 - Average Collision Cost

Collison Severity	Collision Cost (2015 Dollars)	Collision Cost (2019 Dollars)	Proportion of All Urban Collisions (%)	Average Collision Cost (2019 Dollars)
Fatal	5,500,000	5,953,000	0.5	
Injury	150,000	162,500	34.5	**$96,500**
Property Damage	15,000	16,000	65.0	

Table 8 - Summary of Economic Analysis

	Rate of Return		
	3%	**6.5%**	**10%**
Present Value	$133,000	$125,000	$120,000
Average Collision Cost	$96,500	$96,500	$96,500
Minimum Collision Reduction Over Lifespan	**1.38**	**1.30**	**1.25**
Average Yearly Reduction in Collisions	**0.069**	**0.065**	**0.062**

Observed collisions are expected to be altered by multiplicative factors (crash modification factors or CMFs) that are indicative of the countermeasure's performance after implementation [6]. At North American intersections where RLCs have been installed, the crash modification factors associated with collisions resulting in a fatality, an injury or property damage are 0.76 [7], 0.88 [8], and 1.01 [9], respectively. The CMFs associated with crash severities are summarized in Table 9.

Table 9 - Crash Modification Factors for Red Light Camera Treated Intersections

Collision Severity	Collision Modification Factor
Fatal	0.76
All Injuries	0.88
Property Damage	1.01

The annual number of RLR incidences that must occur to ensure the countermeasure is economically feasible (i.e. how many red light violations must occur to warrant RLCs) was determined by relating RLR frequency with observed, expected, and prevented collisions. First, the yearly occurrence of RLR was predicted at each study location using Equations 1 and 2. Secondly, the expected number of annual collisions to occur after RLCs are installed was calculated for each study intersection using Equation 4. Next, the number of red light violations that must occur to assure the minimum reduction in annual crashes is met was also calculated for each study intersection using Equation 5. Lastly, the threshold value for the warrant system was determined red light violations per year using Equation 6. This was repeated three times with respect to each rate of return to frame a sensitivity analysis as shown in Table 10. The threshold value represents the minimum number of red lights that must be run in order to warrant RLCs.

$$EC_i = (OFC_i * CMF_F) + (OIC_i * CMF_I) + (OPDC_i * CMF_{PD}) \quad [4]$$

$$S_i = \frac{R + EC_i}{\left({}^{Observed\ Col/Yr_i}/_{Predicted\ RLR/Yr_i} \right)} \quad [5]$$

$$TH = \sum_{i=1}^{36} S_i \div n \quad [6]$$

Where:

- ECi is the expected number of annual collisions after RLCs are implemented at intersection i
- $OFCi$ is the observed number of annual collisions that result in a fatality at intersection i
- $OICi$ is the observed number of annual collisions that result in an injury at intersection i
- $OPDCi$ is the observed number of annual collisions that result in property damage at intersection i
- CMF_F is the crash modification factor for fatal collisions (0.76)
- CMF_I is the crash modification factor for collisions resulting in an injury (0.88)
- CMF_{PD} is the crash modification factor for collisions resulting in property damage (1.014)
- S_i is the minimum number of annual red light violations at intersection i
- R is the minimum reduction in annual collisions
- $Observed\ Col/Yr_i$ is the total number of annually observed collisions at intersection i
- $Predicted\ RLR/Yr_i$ is number of forecasted annual red light violations at intersection i (Eq. 2)
- TH is the average number red violation violations that must occur each year to obtain the minimum collision reduction (threshold) (RLR frequency/year)
- n is the sample size (n = 36)

Table 10 – Summary of Threshold Sensitivity Analysis

Rate of Return (*r*)	Minimum Number of Annual Red Light Violations
3%	42,010
6.5%	41,966
10%	41,937
Warrant System Threshold = 42,000	

A worksheet-based warrant system, displayed in Figure 2, was developed as a convenient methodology for practical applications. The resulting worksheet combines the predictive model that forecasts the proportion of RLR incidence, collision modification estimates associated with installing RLCs, and an economic feasibility evaluation. Jurisdictions are encouraged to use the provided worksheet to assess a network of urban signalized intersections to determine appropriate locations for to install RLCs and relative priorities. The procedure to employ the worksheet is as follows:

1. Collect the values for each criterion in the worksheet.
2. Multiply the value collected in Step 1 with the corresponding coefficient.
3. Repeat for each criterion.
4. Determine the proportion of vehicles that run a red light daily (RL%) using the provided predictive model.
5. Define the total daily traffic volume for the intersection (ITV).
6. Determine the how many red lights are run yearly (YRL) using the provided equation.
7. If the frequency of RLR is greater than the threshold value (42,000) then RLCs are warranted based on cost-recovery.
8. If the frequency of RLR is within the range of 30,000-42,000 then RLCs may be warranted based on cost-recovery.

9. If the frequency of RLR is less than 30,000 then RLCs are not be warranted based on cost-recovery.
10. Use engineering judgement and consider specific conditions of the intersection (e.g. PFI) and the results from the worksheet to determine if RLCs should be implemented.

Installation Criterion	**Coefficient**	**Value**	**Coefficient * Value**
Major Street Traffic Volume	-0.0001		**MSTV =**
Approaches with Left Turn Lanes	-0.2615	0 1 2 3 4	**LTL =**
Approaches with Right Turn Lanes	0.0961	0 1 2 3 4	**RTL =**
Annual Right-Angle Collisions	0.1298		**RAC =**
Cycle Length (s)	-0.0094		**CL =**
Intersection Geometry	-0.4901	4 Leg = 1 3 Leg = 0	**IG =**

Percentage of Vehicles that Run a Red Light Daily	$e^{(2.3624+MSTV+LTL+RTL+RAC+CL+IG)}$	**RL% =**

Intersection Traffic Volume (AADT)	**ITV =**

Yearly Red Lights Ran	$\left(\frac{RL\%}{100}\right) * \mathrm{ITV} * 365\ {}^{days}/_{year}$	**YRL =**

Red Light Cameras are not Warranted if YRL ≤ 30,000
Red Light Cameras may be Warranted if 30,000 > YRL < 42,000
Red Light Cameras are Warranted if YRL ≥ 42,000

Figure 2 - Worksheet-based Warrant System

5. CONCLUSIONS

The primary goal of this research was to develop a concise and objective analytical procedure to determine if an intersection is an appropriate candidate for RLCs. A sample of 36 intersections from Fredericton and Moncton, New Brunswick, was selected to evaluate the strength of the relationships between the characteristics of local intersections and the proportion of vehicles that run a red light on a daily basis (dependent variable). For each study location, an RLR study was conducted to determine the daily frequency of observed red light violations and a collision data analysis was completed to assess its current safety performance. In addition, several local characteristics were also collected as potential explanatory variables based on obtainability and their potential to influence RLR frequencies. A statistically significant predictive model was then developed (R^2 = 0.78) to determine the proportion of vehicles that would be expected to run a red light on a daily basis. Subsequently, a warrant system was framed from an economic analysis of prevented collisions attributed to RLCs. Lastly, a threshold value for the warrant system was computed, which represents the minimum number of red light violations that must occur each year to warrant RLCs based on cost-recovery. It is recommended that the provided worksheet be supplemented with engineering judgement to determine if RLCs should be installed.

The resulting methodology combines the predictive model that forecasts RLR incidence, collision modification estimates associated with RLC installations, and a cost-effectiveness evaluation. Consequently, a network of intersections can be evaluated to determine where RLC installation is appropriate along with corresponding relative priorities. Implementing the proposed warrant system will result in a more consistent practice and improved overall safety.

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