INTRODUCTION

In British Columbia, collisions at signalized intersections represent about 50% of the total number of collisions in urban areas (1, 2). Many initiatives have been undertaken to improve the safety of signalized intersections in British Columbia, Canada. One of these initiatives is the Signal Head Upgrade Program, which is part of the Insurance Corporation of British Columbia (ICBC) Road Improvement Program. The Signal Head Upgrade Program is a provincial-wide program that was implemented between 2001 and 2003. The program is aimed at reducing the number of collisions that occur at signalized intersections by improving signal visibility. These improvements include signal lens size upgrade, installation of new backplates, addition of reflective tapes to existing backplates, and installation of additional signal heads.

The Manual of Uniform Traffic Control Devices for Canada (MUTCD) (3), published by the Transportation Association of Canada, requires signal lenses to be round, with a diameter of at least 200 mm. A larger signal lens of 300 mm is required for roads where the 85th-percentile speed exceeds 80 km/h and is recommended for all red indications, arrow indications, signal heads that are located 30 m from the stop line, and black spot locations. Backplates (backboards) are proposed by the manual as a tool to increase signal visibility by making the signal head distinct from its surroundings and decrease confusion caused by the distracting features in the background. The backplates are required for all primary signal heads and recommended for secondary and auxiliary signal heads.

Retroreflective backboard borders have been used for many years in Europe and in Australia (4). The use of retroreflective backplate borders seems to produce safety benefits at a relatively low cost. Based on a project report presented by the National Committee on Uniform Traffic Control of Canada in 2001 (5), a recommendation was proposed to the Canadian MUTCD to add the following statement regarding backboards: “the night-time visibility (conspicuousness) of traffic control signals may be enhanced by adding up to 75 mm border of yellow prismatic retroreflective sheeting . . . around the outside edge of the backboard.”

The U.S. Manual on Uniform Traffic Control Devices (MUTCD) (6), issued by FHWA, states that two alternatives can be used with regard to the diameter size for signal lenses: 200 mm (8 in.) and 300 mm (12 in.). The manual states that for signal faces located more than 45 m from the stop line, for approaches to all signalized locations for which the minimum sight distance cannot be met, and for arrow signal indications, a 300-mm lens should be used for signal indications on approaches where road users view both traffic control and lane-use control signal heads simultaneously if the nearest signal face is between 35 m and 45 m beyond the stop line, unless a supplemental nearside signal face is provided. The manual, however, prohibits using a 200-mm red lens with either a 300-mm green lens or a 300-mm yellow lens. Using three 300-mm signal lenses was proposed for approaches with 85th-percentile approach speeds exceeding 60 km/h (40 mph), approaches where a traffic control
signal might be unexpected, all approaches without curbs and gutters where only post-mounted signal heads are used, and locations where there is a significant percentage of elderly drivers.

The manual suggests that the use of backplates enhances the contrast between the traffic signal indications and their surroundings for both daytime and nighttime conditions, which is also helpful to elderly drivers. Therefore, it suggests the use of a signal backplate on signal faces viewed against a bright sky or bright or confusing backgrounds.

The U.S. National Committee on Uniform Traffic Control Devices has reviewed the Canadian research that deals with adding reflective tapes to backplates (1, 2) and recommended to FHWA that text be added to the next edition of the MUTCD to allow the optional use of a yellow retroreflective strip no wider than 75 mm (3 in.) around the perimeter of the face of backplates to project a rectangular appearance at night (4). The committee states that the minimum width of a retroreflective tape is 25 mm and the maximum is 75 mm. The other requirements for the retroreflective tapes (e.g., type of material) were not specified; instead, the committee recommended that retroreflective tape capable of reflecting light at overhead positions be chosen.

PREVIOUS WORK

Considerable research exists on traffic signal visibility (7–12). Most of these studies employed laboratory or controlled field testing to determine the effect of factors such as signal lens size, backplates, weather conditions, and driver characteristics on the visibility of traffic signals. Cole and Brown (7) indicated that signal visibility was insensitive to signal lens size and that only intensity affects visibility. This intensity can be obtained by using higher-intensity sources in 200-mm lenses. However, in practice larger signals are used to increase the light output of the signal so that it can be seen at a greater distance (8). The use of backplates was found to reduce the intensity required by about 25% to 40% at distances of about 100 m and greater reductions were found at shorter distances (7, 9). King (10) found that signal visibility was relatively unaffected by signal lens size and intensity for nighttime operation. However, he indicated that signal type, a variable that combines both lens size and illumination intensity, has a significant effect on signal visibility for daytime operations. King (10) also introduced color as the most dominant factor that influences signal visibility during daytime operation. Freedman (11) supported King’s findings by stating that reduced signal luminance had no significant effect on the response of drivers from different age groups, which accordingly means that luminance does not influence signal visibility.

Although the literature on signal visibility is extensive, few studies have been carried out on the potential safety benefits of improving signal visibility. In a simple before-and-after analysis carried out by Kassan and Crowder (12), improved signal visibility reduced right-angle collisions by 32% to 57% and rear-end collisions by 44% to 86%. However, the same study showed significant increases between 33% and 98% for other collision types. Craven (13) also used a simple before-and-after
analysis to investigate the safety performance at 24 signalized intersections after a general signal upgrading was performed that included increasing lens size from 200 mm to 300 mm and mounting the signal heads at the proper height and proper locations as stipulated in the MUTCD. His results showed a reduction of 10% to 40% in total number of collisions per site and a 25% overall reduction at all sites. Wainwright (14) found that using 300-mm lenses has shown safety benefits in Michigan and North Carolina. However, the quantification of these safety benefits was not presented. Ogden (15) presented potential collision reduction factors for various roadway treatments. He proposed that improving signal visibility could reduce rear-end collisions by 30% to 40%.

Using an improved signal head design, Sayed et al. (1) found that total collisions were reduced by about 24% and that both fatal and injury collisions were reduced by about 16% in 10 urban signalized intersections in British Columbia. The improved signal head design used in the study comprised a 300-mm lens for green, amber, and red lights in addition to a reflective tape of 50 mm on the outer edge of the backplate. The results of this study contributed to a new standard design in British Columbia, that is, use of three 300-mm lenses rather than the 300-200-200 mm design previously used (5).

A study carried out by Sayed and deLeur (2) investigated the safety performance of 17 rural signalized intersections in British Columbia after 75-mm reflective tape was added on the outer edge of the signal backplate. This improvement was suggested as a tool to increase signal visibility by framing the signal head. The results revealed a significant reduction of about 15% in the total number of collisions.

OBJECTIVES AND METHODOLOGY

As mentioned earlier, few studies have been carried out on the potential safety benefits of improving signal visibility in terms of collision reduction. The majority of these studies employed simple before-and-after evaluations (12, 13). Other studies (1, 2) evaluated a small number of locations and did not evaluate the safety impacts on specific collision types. The objective of the current study is to evaluate the safety impacts associated with improved signal visibility for 139 urban signalized intersections. All intersections were four-leg intersections and had either three or four lanes on each approach with a posted speed of 50 km/h. The safety impacts are evaluated for both severe (injury + fatal) and property-damage-only (PDO) collisions and also for daytime and nighttime collisions.

A simple cause-and-effect relationship is rare in road safety. Usually, several other factors operate simultaneously and may influence road safety performance. Therefore, the effect of these other factors should be separated from the treatment effect. These confounding factors include history, maturation, and the regression to the mean (16). History refers to the possibility that factors other than the countermeasure being investigated caused all or part of the observed change in collisions. Maturation refers to the effect of collision trends over time. The regression to the mean refers to the tendency of extreme events to be followed by less extreme values, even if no change
has occurred in the underlying mechanism that generates the process. The methodology adopted in this study is based on the work of Sayed et al. (16–18) and Hauer (19). The method corrects for regression-to-the-mean effects, which is an important consideration in road safety analysis, by using an empirical Bayes (EB) technique. The methodology also uses before-and-after collision and traffic volume data for a comparison group to correct for the confounding factors of history and maturation.

The evaluation methodology employs collision prediction models, which are mathematical models that relate the collision frequency experienced by a road entity to various traffic and geometric characteristics of this entity. The models are developed by using certain statistical techniques and have several applications such as evaluating the safety of various road facilities, identifying collision-prone locations, and evaluating the effectiveness of safety improvement measures. Historically, two statistical modeling methods have been used to develop collision prediction models: conventional linear regression and generalized linear regression. Conventional linear regression assumes a normal distribution error structure, whereas a generalized linear modeling (GLM) approach assumes a nonnormal distribution error structure (usually Poisson or negative binomial). Recently, generalized linear regression modeling has been used almost exclusively for the development of collision prediction models since conventional linear regression models lack the distributional property to adequately describe collisions. This inadequacy is due to the random, discrete, nonnegative, and typically sporadic nature that characterizes the occurrence of collisions.

The mathematical form used for any accident prediction model should satisfy two conditions. First, it must yield logical results. A linear model form often leads to the prediction of a negative number of collisions. It is therefore recommended that a nonlinear model form be used for accident prediction. The model form must also ensure a prediction of zero accident frequency for zero values of the exposure variables. The second condition that must be satisfied by the model form is that in order to use generalized linear regression in the modeling procedure, there must exist a known link function that can linearize this form for the purpose of coefficient estimation (20). These conditions are satisfied by a model form that consists of the product of powers of the traffic volumes. This type of model has been shown to be more suitable to represent the relationships between accidents and traffic volumes at intersections (19). The prediction model structure used in this study relates the frequency of collisions to the product of traffic flows entering the intersection:

\[ E(\Lambda) = a_0 V_1^{a_1} V_2^{a_2} \]  

(1)

where

\[ E(\Lambda) = \text{expected collision frequency (collisions/3 years)}, \]

\[ V_1, V_2 = \text{major- and minor-road traffic volume (annual average daily traffic), and} \]

\[ a_0, a_1, a_2 = \text{model parameters}. \]
The variance of the expected collision frequency is given by

$$\text{Var} (\Lambda) = \frac{E(\Lambda)^2}{\kappa}$$  \hspace{1cm} (2)

where $\kappa$ is the negative binomial parameter of the collision prediction model.

The reduction in the number of collisions at the treatment sites can be calculated by using the odds ratio (OR) according to Equation 3. The effect of the treatment is determined by subtracting 1 from the OR, as shown in Equation 4.

$$\text{OR} = \frac{A/C}{B/D}$$  \hspace{1cm} (3)

treatment effect = $\text{OR} - 1$  \hspace{1cm} (4)

where

$A$ = number of collisions in comparison group during period before improvement,

$B$ = EB estimate of collisions in treatment site had no treatment taken place,

$C$ = number of collisions in comparison group during post-improvement period, and

$D$ = number of collisions in treatment group during postimprovement period.

All quantities in the OR are observed quantities (with assumed Poisson distribution), with the exception of quantity $B$, which is calculated. Therefore, the major work involved in evaluating the benefits of a certain treatment basically is determining the quantity $B$, which is calculated by utilizing collision prediction models and the EB refinement procedure. The EB safety estimate and its variance for a location $i$ are calculated as follows:

$$\left( \text{EB}_i \right)_b = \gamma_i \cdot E(\Lambda_i) + (1 - \gamma_i) \cdot (y_i)$$

$$\text{Var}(\text{EB}_i)_b = \gamma_i \cdot (1 - \gamma_i) \cdot E(\Lambda_i) + (1 - y_i)^2 \cdot (y_i)$$  \hspace{1cm} (5)
\[ \gamma_i = \frac{\frac{E(\Lambda_i)}{E(\Lambda_i) + \text{Var}(\Lambda_i)}}{1 + \frac{\text{Var}(\Lambda_i)}{E(\Lambda_i)}} = \frac{1}{1 + \frac{\text{Var}(\Lambda_i)}{E(\Lambda_i)}} \]  

(6)

where \( \kappa \) is the negative binomial parameter of the collision prediction model, and \( \gamma_i \) is the observed collision frequency in the before period for location \( i \).

The value \( B \) in the OR (Equation 3) is calculated by using Equation 7 following Sayed et al. (16):

\[ B = (EB_i)_a = (EB_i)_b \times \frac{E(\Lambda_i)_a}{E(\Lambda_i)_b} \]  

(7)

where

\( (EB_i)_a \) = EB safety estimate of treated site \( i \) in after period if no treatment had taken place,

\( (EB_i)_b \) = EB safety estimate of treated site \( i \) that occurred in before period,

\( E(\Lambda_i)_a \) = collision frequency given by collision prediction model for treated site \( i \) using its traffic flows in after period, and

\( E(\Lambda_i)_b \) = collision frequency given by collision prediction model for treated site \( i \) using its traffic flows in before period.

To get the expected value and variance of the OR, the method of statistical differentials is used, as follows (16):

\[ E\{Y\} = Y + \left[ \sum_1^n (\partial^2 Y/\partial X_i^2) \text{Var}\{X_i\} \right]/2 \]  

(8)

\[ \text{Var}\{Y\} = \left[ \sum_1^n (\partial Y/\partial X_i)^2 \text{Var}\{X_i\} \right] \]  

(9)
DATA DESCRIPTION

The evaluation of safety impacts of the proposed improvements requires two sets of data: collision data and traffic volume data for the before and after periods. These data are required for two groups of locations: the treatment group and the comparison group.

Treatment and Comparison Locations

All locations in the treatment and the comparison groups were selected to be typically four-leg intersections. Initially, the treatment group data included 171 intersections in 8 municipalities: the British Columbia cities of Burnaby, Coquitlam, Kelowna, New Westminster, North Vancouver, and Surrey; the district of Maple Ridge; and the township of Langley. All these municipalities participated in the ICBC Signal Head Replacement Program between 2001 and 2003. The treatment sites from Maple Ridge and Langley were excluded from the analysis because they lacked comparison site data. Comparison group data for the other municipalities could not be used for Maple Ridge and Langley since they represent different environments. Therefore, the final treatment group included 139 intersections. The distribution of the treated sites among the six municipalities by different countermeasure types is presented in Table 1.

<table>
<thead>
<tr>
<th>Countermeasure</th>
<th>B</th>
<th>C</th>
<th>K</th>
<th>NW</th>
<th>NV</th>
<th>S</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Signal lens size upgraded and added reflective tape to existing backboards</td>
<td>39</td>
<td>6</td>
<td>22</td>
<td>16</td>
<td>0</td>
<td>15</td>
<td>98</td>
</tr>
<tr>
<td>Signal lens size upgraded and new backboards installed, with reflective tape</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Signal lens size upgraded new signal heads installed, and added reflective tape to existing backboards</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Signal lens size upgraded new signal heads installed</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Signal lens size upgraded only</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Added reflective tape to existing backboards only</td>
<td>0</td>
<td>0</td>
<td>11</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>Total</td>
<td>39</td>
<td>19</td>
<td>22</td>
<td>27</td>
<td>10</td>
<td>22</td>
<td>139</td>
</tr>
</tbody>
</table>

B = Burnaby; C = Coquitlam; K = Kelowna; NW = New Westminster; NV = North Vancouver; S = Surrey.
A comparison group was prepared for each group of sites that belong to the same municipality. The comparison sites were selected to be generally in close proximity to the treatment sites and to be subject to the same traffic and environmental conditions as the treatment sites. The size of each comparison group ranged from 7 to 40 sites. A total of 85 sites were used in the comparison groups. There were no significant changes in the traffic volumes between the before and after periods for the comparison sites.

**Collision and Traffic Volume Data**

Intersection collision data based on insurance claim records from the ICBC were used in the study rather than police-reported collision data, which have suffered a period of deterioration in recent years in British Columbia and have deteriorated in an inconsistent manner. The automobile insurance claim data are current and comprehensive and are considered quite reliable for intersection locations (2, 16, 21). DeLeur and Sayed (21) found that the claim data can be used in place of the degraded collision data to evaluate road safety and applied in a similar manner as collision records. Considerable effort was undertaken to collect reliable traffic volume data for the treatment and the comparison sites. Collision data were available for 1999 to 2004, and different implementation years of 2001, 2002, and 2003 were considered for the treated locations. The number of before and after periods for different implementation years are as follows:

<table>
<thead>
<tr>
<th>Implementation Year</th>
<th>Before Period</th>
<th>After Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>2002</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>2003</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

**RESULTS**

Five collision prediction models were developed with the GLM approach as described by Sawalha and Sayed (18, 20) and by Hauer (19). The models are used to predict severe (fatal and injury), PDO, daytime, nighttime, and total collisions. Available data did not support the evaluation of specific collision types, such as rear-end crashes.

The error structure of the models is assumed to follow the negative binomial distribution. Data on traffic volumes and 3 years of collision frequency were collected for 175 intersections in British Columbia and used to develop the models. The five models and their parameters are shown in Table 2.

Two statistical measures were used to assess the goodness of fit of the models: the Pearson $\chi^2$-statistic and the scaled deviance (SD), defined in Equations 12 and 13. Both the Pearson $\chi^2$ and SD are asymptotically $\chi^2$-distributed with $n-p$ degrees of freedom.
The goodness-of-fit measures of the models are shown in Table 3. All models showed good fit to the data, especially after a small number of outliers (two to three outliers) was excluded.

The results of the evaluation are summarized in Table 4. As shown, the results indicate significant reductions of 8.5%, 5.9%, 6.6%, and 7.3% for PDO, daytime, nighttime, and total collisions, respectively. Severe collisions showed a nonsignificant reduction of 2.6%. Figure 1 shows the reduction in different collision types for each municipality.
DISCUSSION AND CONCLUSIONS

The safety impacts of improving signal visibility at urban signalized intersections was investigated. The visibility improvements included one or a combination of the following upgrades: signal lens size, new backboards, reflective tapes added to existing backboards, and additional signal heads. A total of 139 intersections were evaluated. The analysis was carried out by using collision data based on insurance claim records from the ICBC. These data are considered more reliable than police-reported collision data. Collision prediction models, comparison group data, and EB analysis were utilized in the evaluation to account for various confounding factors. The results of the evaluation showed significant safety improvements at the treated intersections as a result of improved signal visibility.

Collision reductions of 8.5%, 5.9%, 6.6%, and 7.3% for PDO, daytime, nighttime, and total collisions, respectively, were found. However, severe collisions showed a nonsignificant reduction of 2.6%. The reduction in nighttime collisions, for which the improvements are likely to be more effective, is higher than that of daytime collisions. As well, the higher reduction in PDO collisions compared with severe collisions is consistent with the results of previous studies (1, 13).

The results are generally consistent with the studies found in the literature, which indicated that improving signal visibility is an effective safety treatment. However, the collision reductions reported in this study are generally smaller than those reported earlier (1, 2, 12, 13). Two of these studies (12, 13) employed a simple before-and-after evaluation, which is likely to overestimate the safety impacts. The difference between the results reported in this study and those reported earlier by Sayed et al. (1) and by Sayed and deLeur (2) may be attributed to two main factors.
The first is the difference in the sample size. Sayed et al. (1) evaluated 10 intersections, whereas Sayed and deLeur (2) evaluated 17 intersections compared with 139 intersections evaluated in the current study. Second, the intersections evaluated in both earlier studies (1, 2) were highway intersections with higher posted speeds than the intersections evaluated in this study. This difference may indicate that improving signal visibility can be more effective for intersections with higher speeds, which is consistent with the recommendations of the MUTCD.

Overall, the results of this study show that improving signal visibility is effective in enhancing safety at urban signalized intersections, and consideration should be given to expanding its use.

REFERENCES