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Operating a mobile photo radar enforcement program: A framework for site selection, resource allocation, scheduling, and evaluation

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ABSTRACT

This paper introduces a systematic, data-driven framework by which to operate a mobile photo radar enforcement (MPRE) program, consisting broadly of site choice, enforcement resource allocation and scheduling, and evaluation. The overall goal is provide a framework for operating an MPRE program that is well-defined and replicable, in order to improve efficiency in deploying finite enforcement resources and efficacy in improving traffic safety. To illustrate the process, the proposed program was applied to simulate a deployment plan for one month using data from the City of Edmonton. The results of program application were assessed against the results of the existing MPRE program in place in May 2014, using several candidate short-term evaluation measures. Based on the results, it is expected that with implementation of the proposed program, the City of Edmonton's MPRE program may observe moderate to high improvements in travel distance efficiency and coverage of sites with safety issues. The promising test results do further indicate the need for a full-scale, real-life deployment of the proposed program. This proposed MPRE program design framework can provide planners, engineers, and law enforcement professionals with a systematic, analytic, and data-driven process by which to operate a MPRE program. Despite that the design framework was built in response to the needs of the City of Edmonton's current MPRE program, its development was generalized for adaptation and adoption within any jurisdiction looking to begin a new program, or make improvements to an existing one, in their pursuit of greater traffic safety.

1. Introduction

This paper introduces a systematic, data-driven procedure by which to operate a mobile photo radar enforcement (MPRE) program, consisting broadly of site choice, enforcement resource allocation and scheduling, and evaluation. The overall goal is to provide a well-defined and replicable framework to operate an MPRE program, with the goals of improving efficiency in deploying finite enforcement resources and efficacy in improving traffic safety. The results of a simulation study demonstrate that the proposed framework may lead to greater efficacy in violations reduction, and efficiency gains with respect to resource usage.

MPRE combines traditional manned speed enforcement with the use of an automated camera detection system installed in a vehicle to capture speed violators. MPRE has been adopted in many jurisdictions throughout the world, and has been demonstrated to achieve desired outcomes in reducing speeding and speed-related collisions. In France, it was found that with MPRE, fatal and non-fatal collisions were reduced by 21% and 26%, respectively (Carnis and Blais, 2013). In the city of Charlotte, North Carolina, collisions at locations with mobile photo enforcement were observed to have dropped by an average of 10%; in addition, the mean, median, and 85th percentile speeds measured at enforcement locations were observed to have decreased by at least 0.5 mph (Cunningham et al., 2008). In Washington D.C., the mean speeds of traffic at enforced locations decreased by 14%, with an 82% reduction in the number of vehicles exceeding the speed limit by 10 mph (16.1 kph) (Retting and Farmer, 2003). In British Columbia, Canada, speed-related collisions were observed to decline 25% at enforced locations (Chen et al., 2002). In Victoria, Australia, a 22% reduction in all collisions

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was observed, while the number of injury collisions fell by 38% (Coleman and Paniati, 1995).

Despite the safety improvements documented through the application of MPRE programs, it is unclear how program design details impact efficacy in improving safety – in other words, how finite program resources can be assigned and utilized in such a way as to provide maximum safety impacts. A comprehensive review of both the academic literature and state-of-practice on various topics related to MPRE shows that many studies document the procedures, methodologies, and performance measures used to evaluate the effectiveness of MPRE programs. However, there is little information about systematic design processes that guide initialization or operation of MPRE programs. As a result, this paper aims to address this gap in the literature by presenting a framework for MPRE program operations and evaluation. The proposed site selection, prioritization, enforcement scheduling, evaluation, and adjustment process is a data driven, evidence-based program design. It incorporates updated program performance information, and traffic and enforcement data, to achieve well-defined goals. The framework can be used to initiate a new program where none exists, or to modify an existing program.

The proposed program was applied to simulate a deployment plan for one month using historical data from the City of Edmonton, Canada. Through this test application, it is demonstrated that the proposed program may offer improvements over the existing program, in terms of coverage of collision and speed violation prone sites and travel distance efficiency. As the simulation test demonstrates that benefits may be gained from a real-life deployment of such a program, the City of Edmonton will trial a real-life deployment of the proposed program.

2. Literature review

This review covers the literature documenting the effects of MPRE on speeding and collisions, general and specific deterrence effects, and resource scheduling and deployment strategies. Most documented studies of MPRE evaluate the influence of MPRE programs on vehicle speeds and collisions. Studies have demonstrated that MPRE can reduce mean vehicle speeds by 2%–14% (Retting and Farmer, 2003; Goldenbeld and Schagen, 2005; Berkuti and Osbuen, 1998; Cities of Beaverton and Portland, 1997). The percentage of vehicles exceeding the speed limit tolerance was reduced from 23% to 3% in Victoria, Australia (Coleman and Paniati, 1995). In San Jose, California, MPRE resulted in a 15% reduction in the number of drivers speeding 10 mph (16.1 km/h) over the speed limit (Davis, 2001). Numerous studies have also shown MPRE to reduce the number of serious collisions resulting in injuries and fatalities (Carnis and Blais, 2013; Retting and Farmer, 2003; Chen et al., 2002; Coleman and Paniati, 1995; Gains et al., 2004; Christie et al., 2003).

The effectiveness of a MPRE program is the outcome of unavoidability, immediacy, and punishment severity (Carnis and Blais, 2013; Zaal, 1994). MPRE impacts driver behavior through both general and specific deterrence mechanisms (Zaal, 1994). Potential violators are more likely to comply with speed limits than risk offending when they observe other individuals being penalized; this is called general deterrence (Tay and Barros, 2011). General deterrence is also attributed to MPRE as well as general dangerous driving education and awareness campaigns. Specific deterrence is the phenomenon where a driver experiences detection and punishment firsthand (Tay and Barros, 2011). One study suggests that because general deterrence is more prominent than specific deterrence, enforcement should primarily aim at achieving greater general deterrence. This can be achieved by focusing on high-risk time periods and locations, using a mix of highly visible and less visible forms of enforcement to improve enforcement publicity and unpredictability, and implementing a plan for long-term enforcement activity (Keall et al., 2001). Within the City of Edmonton, it was shown that as the number of enforced sites and issued tickets increased (thereby promoting greater awareness amongst the driving public of the MPRE program), the number of speed-related collisions decreased. Collision reductions were associated with a MPE program that promoted higher location coverage, more frequent checks, and more issued tickets (Li et al., 2015). Because of the varied elements that contribute to general deterrence, and the complex mechanism by which they contribute, it can be difficult to pinpoint how general deterrence is achieved.

Guidance for selecting enforcement is often provided by governments; one example is the Province of Alberta's Automated Enforcement Guidelines (Alberta Justice and Solicitor General, 2014). Usually, MPRE is deployed at locations with demonstrated records of collisions, speed limit violations, and public complaints about speeding (Carnis, 2011; Cameron and Delaney, 2006). In addition it can also be deployed when special requests have been made by local governments and organizations, and at locations where traditional speed enforcement methods are infeasible or have been found to be ineffective. Although methodologies for enforcement site identification abound in the literature, much less attention has been given to the development of systematic, quantitative site selection and deployment processes for MPRE.

The number of deployment hours, deployment frequency, number of enforced sites, and number of violations or issued tickets – amongst other metrics – may be considered for use in MPRE program evaluation (Goldenbeld and Schagen, 2005; Nilsson, 2004; Chen et al., 2000). A study was performed in the State of Victoria where enforcement levels were varied, to map out a relationship between the level of speed violations and casualty crashes (Cameron et al., 2003). Additionally, a relationship between camera hours per month and casualty crashes in Queensland within 2 km of camera sites was established (Newstead et al., 2004). Another study looked at establishing city-level relationships between three selected enforcement performance indicators (number of enforced sites, average check length, and number of issued tickets) and the City of Edmonton's MPRE program's safety outcomes (Li et al., 2015). However, a causal relationship between deployment metrics and changes to speed violations at a disaggregate level have not been established. Although long MPRE deployment durations as well as frequent visits (both resulting in high site exposure) usually result in significant reductions to speed limit violations and collisions, either may not be possible to implement as most jurisdictions have limited resources available for enforcement activities. Also, it may be unnecessary to maintain long deployment durations at all sites, given that the impacts of enforcement diminish with drivers' increasing awareness of detection (Christie et al., 2003). After enforcement ends at a particular site, a residual effect (halo effect) will remain three to four days or even two to eight weeks before drivers' behaviors return to the state observed prior to enforcement (Chen et al., 2000; Vaa, 1997). Optimal deployment frequencies can be determined based on the time halo effect of MPRE.

Both fixed and randomized scheduling methods have been employed (Carnis and Blais, 2013; Carnis, 2011; Cameron and Delaney, 2006; Newstead et al., 1999; Leggett, 1997). A fixed scheduling method determines all details about when, where and in what order to conduct enforcement activities, based on pre-defined protocols and rules of program operations. In randomized scheduling, randomness is introduced into the protocols that decide when, where and in what order enforcement activities are conducted. This is typically achieved by allowing operators some autonomy in making these decisions. Randomized scheduling is surmised to achieve the same levels of collision reduction as fixed scheduling, but with less enforcement resources (Leggett, 1997; New Zealand Traffic Camera Office, 1995). A number of Australian MPRE programs have demonstrated that randomized scheduling is effective in reducing serious injuries and fatalities, even with low deployment intensity (Cameron and Delaney, 2006; Newstead et al., 1999; Leggett, 1997; Newstead and Cameron, 2003). The randomized scheduling used in Australia allows enforcement units to be deployed at randomly chosen locations and at random times. The resulting low predictability enhances the perceived risks of apprehension, and consequently encourages drivers to comply with speed regulations (Newstead et al., 1999). In order to promote maximum usage of limited equipment and labor resources for MPRE, this paper proposes the design of a new MPRE program operations framework that explicitly targets high-risk locations while striving to maintain the perception of randomness.

3. Mobile photo radar enforcement (MPRE) program framework

This section proposes a design for a MPRE operational program, which includes four major steps for scheduling resources and evaluating program performance: 1) data gathering, 2) application of a multi-criteria screening methodology to identify and prioritize potential enforcement sites, 3) a method for resource scheduling and deployment, and 4) evaluation.

The development and design process for each component shown in the figure is detailed in the sections that follow (Fig. 1).

3.1. Data gathering

Where a MPRE program is currently in place, the following information should be collected when available.

1. MPRE program details: including information on institutional structures, management protocols, program staffing, and equipment availability;
2. Traffic data: historical collision, vehicle speed, speed limit violation, and traffic volume data for potential enforcement locations, which include currently enforced sites and as well as additional candidate sites with potential speeding and safety issues;
3. Historical deployment data (ideally at least 12 months): enforced site locations by date and time of day, durations and frequency of site visits, etc.

3.2. Site identification

Three major questions arise during the enforcement site identification and selection process:

1. What types of locations should be included in the MPRE site pool?
2. What factors should be considered when screening candidate locations?
3. How should potential locations be prioritized?

Enforcement locations are categorized into two groups based on the predominant reason for enforcement. The first group consists of locations with confirmed speeding problems – these locations have relatively high numbers of speed limit violations and/or speed-related collisions. Locations in this first group are referred to as speeding problem (SP) sites in this paper. An SP “site” is in fact defined as a roadway segment between two intersections. SP sites are further categorized by roadway type as they can be located on arterial, collector, or local roads. The second group of enforcement locations consists of special concern (SC) sites. These sites require enforcement to address safety concerns brought to attention by local organizations, private citizens, or other parties. SC sites can be within construction zones, in the vicinity of special events (festivals, sporting events, etc.) and neighborhood facilities (schools, playgrounds, community centers, etc.). In the City of Edmonton (CoE), the speeding problem (SP) site pool is further comprised of photo radar (PR) and speed survey (SS) sites. PR sites are those at which MPRE has been previously deployed and where speeding problems are confirmed to exist or have existed. SS sites are locations undergoing speed surveys as a result of public complaints about speeding. SS site have not yet had MPRE deployments but are potential candidates should survey results warrant and deployment is physically possible. The site types are summarized in Fig. 2.

Candidate locations for MPRE should be screened based on the frequency of (midblock) collisions, frequency of speed limit violations, and road type. Midblock collision counts are an important consideration in allocating deployment resources, for two major reasons. First, the safety continuum shows that collisions represent the least frequent but most dangerous occurrences. Therefore, the prevalence of speed-related collisions – specifically, the consistent occurrence of these events – indicates that there is an underlying problem that needs investigation.

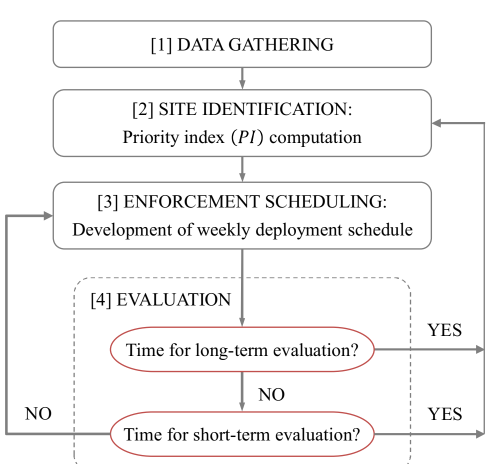


Fig. 1. MPRE program decision process & framework.

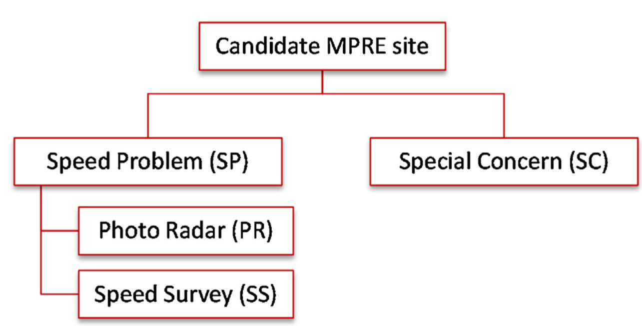


Fig. 2. Candidate sites for photo radar enforcement.

Second, a MPRE program that does not specifically aim to target high-speed collision locations is not likely to garner public support, given that MPRE programs can be viewed unfavorably for various reasons and are therefore politically difficult. In addition, the effects of MPRE can spill over into adjacent intersections due to the distance halo effect, but exactly how MPRE impacts intersection safety has not been explored in previous studies – hence, the focus on midblock collisions. The frequency of speed limit violations can reflect the severity of speeding issues at a given site. MPRE has been proven to mitigate speeding issues (Retting and Farmer, 2003; Goldenbeld and Schagen, 2005; Berkuti and Osbuen, 1998; Cities of Beaverton and Portland, 1997).

MPRE locations are ranked according to their Priority Index (*PI*) values, computed using the method described below. The method is developed based on the equivalent-property-damage-only (EPDO) average crash frequency method (AASHTO, 2010). The EPDO average crash frequency method ranks locations by assigning weights to collisions according to severity; the method includes the impacts of collision frequency and severity (AASHTO, 2010). However, it is noted that the costs estimated and assigned to fatal collisions are much higher than other collision severity types, and also vary significantly from one jurisdiction to another. For example, the cost per fatal collision in North Carolina was estimated to be over 10 million US dollars in 2013 (NCDOT, 2013). This high fatal collision cost could lead to a heavy enforcement emphasis to sites that have experienced fatal collisions, as they would have very high EPDO crash frequencies. To overcome this issue, MPRE program managers could adopt the Kentucky Formula, which is method to reduce the undue emphasis on fatal collision sites in computing EPDO frequencies. The formula does not use costs as weights for different collision severities, but proposes a constant weighting factor of 9.5 for fatal and severe injury collisions and 3.5 for moderate injury collisions (Findley et al., 2015). In general, when computing EPDO crash frequencies, MPRE managers should use collision classification, or adopt direct collision costs or weighting factors based on their experience and local knowledge.

In addition, frequency of speed limit violations is also accounted for in the Priority Index (*PI*) and weighted by their relative cost to property-damage-only (PDO) collisions. In computing the *PI*, it is recommended that a minimum of one year of collisions and speed limit violations data is used (AASHTO, 2010) when possible, which is also consistent with the long-term evaluation plan described in Section 3.4.2. The *PI* computation process is described in the following steps.

3.2.1. Normalize midblock collision and speed limit violation data

The number of midblock collisions and speed limit violations observed for a site (totaled over periods during which MPRE was deployed or a speed survey was conducted) usually vary greatly. Note that from this point forward, midblock collisions will simply be referred to as collisions. Speed limit violation data can only be collected when speed surveys or MPRE are conducted. However, it is assumed that collision data is collected continuously, since many jurisdictions require collisions with property damage greater than a specific threshold to be reported to police.

A site's speed limit violation and collision data are normalized using assigned weights, in order to generate the site's *PI* value. First, the number of speed limit violations per site visit should be divided by total deployment hours to g an hourly speed limit violation rate before a normalized speed limit violation rate is calculated using Eq. (1). Collision counts can be normalized using Eq. (2) without further treatment as they are reported and recorded continuously throughout the year. Second, normalization for road type is done for both speeding problem (SP) and special concern (SC) sites, to eliminate potential biases due to categorical differences in segment length and lane widths.

The normalized values for collisions and speed limit violations at each site are computed as follows (Shyamal and Squire, 2006):

$$V_i{}^* = \frac{V_i/T_i - V_{nt}^{min}}{V_{nt}^{max} - V_{nt}^{min}} \tag{1}$$

$$C_{ij}{}^* = \frac{C_{ij} - C_{ntj}^{min}}{C_{ntj}^{max} - C_{ntj}^{min}} \tag{2}$$

Where:

$V_i{}^*$ = normalized speed limit violations at site *i*, which belongs to road type *t* and site group *n*, $V_i^* \in [0, 1]$;

$C_{ij}{}^*$ = normalized midblock collisions at *i* for severity level *j*,$C_{ij}{}^* \in [0, 1]$;

V_i = total speed limit violations at *i*;

C_{ij} = total midblock collisions at *i*, severity level *j*;

T_i = total deployment hours at *i*;

$V_{nt}^{min}, V_{nt}^{max}$ = minimum, maximum hourly speed limit violations for road type *t* in site group *n*;

$C_{ntj}^{min}, C_{ntj}^{max}$ = minimum, maximum hourly midblock collision at severity level *j* for *t* in *n*;

i = site index;

j = collision severity level, where *F* is fatal, *I* is injury, and *P* is property-damage-only;

t = road type for site *i*, where *A* is arterial, *C* is collector road, and *L* is local road, and

n = site group identifier, where 1 represents SP sites and 2 represents SC sites.

The normalization processes above takes road type (and therefore, to some extent, site length and width) into consideration. When generating a combined score with assigned weights (Step 2), normalization ensures that both collisions and speed limit violations can be considered in this combined score.

3.2.2. Compute urgency index (*UI*) for each site

In this step, each site is assigned an Urgency Index (*UI*), which combines the impacts of speed limit violations and collision frequency and severity, using the following:

$$UI_i = \alpha_j C_{ij}{}^* + \beta V_i{}^* \tag{3}$$

where:

UI_i = urgency index for site *i*;

$C_{ij}{}^*$ = normalized midblock collisions at *i* for severity level *j*;

$V_i{}^*$ = normalized speed limit violation counts for *i*, and

α_j, β = relative weights for midblock collisions of severity *j* and speed limit violation counts, respectively.

The coefficients α and β typically represent the cost per unit of the normalized values (Truong and Somenahalli, 2011; Pulugurtha et al., 2007; De Leur and Milner, 2011). According to a study conducted in Alberta, collision costs consist of both direct and indirect costs (De Leur, 2010). α_j can be set as the ratio of the cost of a collision of severity *j* (DC_j) to that of property-damage-only (DC_P):

$$\alpha_j = \frac{DC_j}{DC_P} \tag{4}$$

Where:

α_j = collision coefficient for collision severity *j*;

DC_j = direct cost of collision with severity level *j*, and

DC_P = direct cost of a property damage only collision.

The speed limit violation coefficient β is the ratio of the estimated cost of a speed limit violation to a property-damage-only collision:

$$\beta = \frac{EC_V}{DC_P} \quad (5)$$

Where:

β = speed limit violation coefficient;

EC_V = estimated cost of a speed limit violation, and

DC_P = direct cost of property-damage-only collision.

The cost of a speed limit violation may be a function of the costs of injury and fatality collision risk resulting from exceeding a speed limit (Ayuso et al., 2010). The greater the speed limit violation, the more likely a collision will occur and the more serious it is likely to be (Nilsson, 2004). Therefore, the cost of a speed limit violation is computed using the following equation:

$$EC_V = p_I DC_I + p_F DC_F \quad (6)$$

where:

DC_I, DC_F = direct cost of an injury collision and fatal collision due to speed limit violation, respectively, and

p_I, p_F = estimated probabilities of an injury collision and fatal collision due to speed limit violation, respectively.

Values for p_I and p_F can be estimated from data.

The cost estimation method can be extended by calculating injury and fatality risk values for each excessive speed category, but only if the required data is accurate and available. Speed violations can be categorized into bins, before normalization. The estimated cost is computed using the following equation:

$$EC_{Vs} = \sum_s (p_{Is} DC_I + p_{Fs} DC_F) \quad (7)$$

where:

EC_{Vs} = estimated cost of traveling within speed limit violation bin s;

s = speed limit violation bin: bin 1 is 0–10 kph (0–6.2 mph), bin 2 is 10–15 kph (6.2–9.3 mph), . . . , bin 5 is 25–30 kph (15.5–18.6 mph), and

p_{Is}, p_{Fs} = estimated probabilities of injury and fatality due to collision, respectively, for s.[1]

Historical speed limit violation data are not always likely to be available for new special concern (SC) sites. In these situations, we consider only collisions when computing *UI*. In addition, it is noted that in calculating estimated speed violation cost (Eqs. (6) and (7)), two collision severities in the broad categories of injury and fatality were considered, because the costs associated with fatal collisions are so much higher than those of injury collisions (no matter the severity). Alternately, a range of costs may be used to represent a range of injury collision severities and classifications, and some enforcement agencies may find this to be a preferred option in estimating speed violations costs.

3.2.3. Compute *PI* for each site

A site's Urgency Index (*UI*), computed using Eq. (3), represents its priority amongst all enforceable sites in regards to its need for enforcement due to speed and safety concerns. As the primary purpose of MPRE at a speeding problem (SP) site is to address speeding issues, $PI = UI$ at SP sites. For special concern (SC) sites, in addition to the severity of speeding issues represented by its *UI*, its *PI* reflects the enforcement required to address special concerns as represented by the Special Requirement Index(*SI*). *SI* is based on the theory of the analytic hierarchy process (AHP), which quantifies the importance of a problem's elements as numerical values compared over the entire range of the problem (Saaty, 1990). A scale consisting of four qualitative urgency levels (low, medium, high, and very high) is adopted to assess the degree of special enforcement required, with numerical values assigned to each level (2, 4, 6, 8, where 2 is low and 8 is very high). Each SC site is assigned a value for *SI*; sub-values are also possible (e.g., 2.1, 3.0, 6.8, 7.2, 7.9, etc.). MPRE program managers/decision-makers should be responsible for assigning *SI* values to SC sites.

For SC sites, *PI* may be computed as a weighted sum of *UI* and *SI*:

$$PI = \omega_1 UI + \omega_2 SI \quad (8)$$

where:

PI = priority index;

UI = urgency index;

SI = special requirements index, indicating the urgency for special enforcement ($=0$ for SP sites), and

ω_1, ω_2 = weights for *UI*and SI, respectively.

The weights ω_1 and ω_2 should be determined by MPRE program managers based on their knowledge of local context and needs.

Once every site in the enforcement site pool has been assigned a *PI*, the speeding problem (SP) and special concern (SC) site groups should each be ranked from highest to lowest *PI* value. All *PI* values and site rankings should be re-assessed after a long-term evaluation of the MPRE program is conducted (evaluation procedures are discussed in Section 3.4). Collision data is not suitable for analysis in short-term periods (i.e. one month) as collisions are usually random events that occur infrequently; as a result, any monthly updates to *PI*s do not include updates to the collisions part of the computation.

3.3. Enforcement resource scheduling

Enforcement resource scheduling involves determining where and when MPRE resources are to be dispatched. There are many candidate methods to deploy personnel and equipment in a MPRE program, including those that rely entirely on enforcement operator experience, completely randomized approaches, and those that optimize to explicitly defined objectives. For example, it is not uncommon for operators to choose sites from a list made by program managers, and decide when and in what order they will visit these chosen sites. The deployment scheduling method proposed in this paper allows operators to maintain this autonomy, in order to minimize disruption of an existing program culture. The proposed random scheduling method is similar to that of the Random Road Watch program in Australia (Leggett, 1997). However, unlike the Random Road Watch program, which aims to cover as many routes as possible by randomly assigning road segments into a weekly schedule, the method proposed here targets a shortlist of sites identified through the site selection process discussed previously. Operators' decisions regarding MPRE deployment scheduling are expected to contribute to the perceived randomness of enforcement.

The deployment scheduling process consists of three parts: development of a monthly candidate site list, allocation of monthly enforcement visits to sites, and development of weekly deployment schedules.

3.3.1. Monthly site list

An enforcement site list should be generated on a monthly basis, based on site *PI* values and the results of a monthly (short-term) program performance evaluation. The monthly site list can consist of both speeding problem (SP) and special concern (SC) sites, the number of each to include in the site list can be decided on by program managers based on observed needs. For example,

[1] We note that values for p_I and p_F can be found in (Ayuso et al., 2010), and are used in Section 4.

say there are a relatively small number of candidate SC sites, and the MPRE program managers have deemed it necessary to give more attention to these sites. In this case, program managers may decide to include the entire set of candidate SC sites in the monthly site list, and fill the remaining spots on the list with SP sites.

The total number of sites in the monthly site list should be based on estimates of resource availability over the upcoming month, including estimates of the number of available equipment (vehicles and devices), operators and their work schedules, and the average anticipated number of sites that should be visited during each shift. The monthly site list can be populated by both SP and SC sites. As mentioned previously, the number of sites from each group to include on the list can be decided upon by program managers.

3.3.2. Weekly job lists

The total number of enforcement visits to make to each of the sites in the monthly site list is based on the estimated enforcement resource availability. Three levels (Levels 1–3) will be designated for SP and SC sites separately, based on *PI* values. Level 1 sites have the lowest *PI* values and therefore are considered low importance; Level 3 sites have the highest values and therefore are considered to be of highest importance; Level 2 are those in between. The number of visits to each site will be determined based on their importance and historical deployment records. In the CoE, based on historical enforcement resources, the number of visits per month designated to Level 1 sites is 1–9, Level 2 is 12–20, and Level 3 is 22–36. The precise number of visits allocated to each site in each level is determined by randomly generating an integer within the visit range.

To ensure schedule adjustments can be made to accommodate changing resource availabilities from week to week, site visits should be distributed weekly to the enforcement squads on enforcement job lists. For example, if five enforcement squads are available for MPRE each week in a four-week month, 20 job lists would be created – one per week, per squad.

3.3.3. Weekly squad deployment schedules

Based on a week's enforcement job list for the squad, the squad leader assigns site visits to each available enforcement operator on the squad. In the CoE, for example, if all nine operators and enforcement units of a squad are available, the squad leader would divide site visits from the weekly job list into sub-lists for each of the nine operators, considering that each operator is required to abide by the following principles:

1. The operators deployed within one shift should be broadly distributed throughout the city to avoid geographic clustering.
2. A site can be visited only once per shift.
3. A site cannot be visited in two sequential shifts.
4. The sites visited by an operator within a shift should be relatively close to one another, to avoid unnecessarily long travel between site visits. However, sites that are located on the same roadway segment but opposite directions should not be enforced in the same shift (by the same or different operators).

If there are major or last minute changes in resource availability within a squad, sites can be offloaded to or accepted by other squads when possible.

The program design ensures that operators have autonomy in planning their site visit schedules, when to visit, how long to stay, and in what order to visit them. However, they will also be provided some guidance in these choices, with site information identified and compiled in the site identification process described previously. In turn, the process of site identification is supported by historical data analysis in the program evaluation, performed yearly (see Section 4 on evaluation procedures). Site-specific information that can guide operators in their decisions (which, when, duration, and order) may include daily and seasonal collision peaks, daily and monthly distributions of speed limit violations, deployment history, and relationships between enforcement intensity and collision reductions (if available).

The above program design ensures that a large portion of MPRE program decisions are maintained within the control of squad leaders and operators. The aim is to maintain a perception of randomness to drivers, by allowing for different MPRE decisions to be made by different parties. Programs that are based on randomized scheduling decisions have been shown to be successful (see Section 2). However, it may be difficult to implement in pre-existing (and even new) MPRE programs, with an existing culture in which operators maintain a relatively high level of control over their daily activities, such as in the City of Edmonton. To ask operators to relinquish this control may be infeasible. However, more high-level administrative control over the deployment plan may be put in place at a later time, possibly utilizing specific techniques to minimize program costs while maintaining the perception of randomness.

In addition, the proposed program schedule design does not account for time and distance halo effects (the latter of which was mentioned earlier, in Section 3.2). Inclusion of these effects was deemed questionable and difficult to justify given the relative lack of empirical evidence. However, an empirical study was conducted through summer 2015 in the City of Edmonton, the results of which may be considered in future versions of the proposed program design.

3.4. Guidelines for evaluation and program adjustment

MPRE program evaluations are necessary to measure program efficacy, as well as to provide inputs for site identification and monthly site lists development.

3.4.1. Short-term (monthly) evaluation

As mentioned previously, the program is to be evaluated on a monthly basis, in order to facilitate adjustments to the site list and deployment instructions from month to month. A monthly evaluation frequency was chosen for short-term evaluation because both weekly and yearly evaluations did not suit our purposes. A weekly evaluation was determined to be too frequent to meaningfully inform the site list adjustment process. However, a yearly evaluation was deemed too infrequent for making program adjustments (by assessing sites' speed, collision and deployment data). Moreover, a monthly frequency for short-term evaluation is consistent with programs in other jurisdictions (Newstead et al., 1999; Tay, 2010).

Short-term evaluation involves analysis of deployment-related statistics and the impacts of MPRE on speed limit violations at sites, in order to evaluate program efficiency and efficacy. Deployment statistics include the number of enforced sites, site visit frequency, average time spent per site per visit, and speed limit violation rates. Because it is difficult to observe significant changes in the number of collisions within such a short period (because they are random and relatively infrequent events), only speed limit violations are used as a measure of program efficacy. The measures reflecting the effects on speed limit violations include the number of speed limit violations detected per site visit per month and hourly distribution of speed limit violations.

In addition, other deployment-related performance measures used by other jurisdictions are candidate measures, including spatial distribution of the visited sites, the percentage of enforced sites for each type, utilization of both vehicle and personnel resources, and compliance to the enforcement schedule (Newstead et al., 1999; Leggett, 1997).

The monthly adjustment to the monthly site list is informed by changes in speed limit violation rates, resource availability, and enforcement capability. For SP sites, those where speed limit violations are not observed to decrease are retained in the monthly site list. Sites that are observed to have decreasing speed limit violations can be removed from the list and replaced by sites newly selected from the preliminary monthly site list. SC sites with speed limit violations that do not drop, or those that still require enforcement due to specialized needs, should be retained. If the special requirement has been met or a significant reduction in speed limit violations is observed, the site can be removed from the list. A pre- and post-deployment speed survey can be conducted, using a two-sample *t*-test used to determine whether the decrease in mean speed is statistically significant. The test is a simple tool for program managers to decide the minimum speed limit violation reduction considered to be adequate for ceasing enforcement. The decision can also be based on criteria used by other MPRE programs. More sites can be included in the monthly site list if more enforcement resources are added. Again, the total number of sites should be in line with estimated resource availabilities for the month.

3.4.2. Long-term evaluation and adjustment

Assessing changes in the number of collisions is not meaningful when assessed at monthly frequencies; therefore, a long-term evaluation plan is also required. This long-term evaluation might be performed at 12-month intervals (Newstead et al., 1999) or possibly longer, depending on specific needs and constraints. The long-term program evaluation consists of assessing city-wide collisions and speed survey data (which could be considered an assessment of general deterrence efficacy), as well as MPRE deployment statistics. The long-term evaluation should consist of the following:

- Assessment of changes in speed limit violations at enforced and unenforced sites;
- Assessment of changes to collision frequency and severity, at site and city-wide levels;
- Assessment of changes in speed, such as reduction in mean speed, compliance to speed limits, and speed variance.

Other program evaluation measures may be developed based on the following:

- Geographic distribution of high collision and speeding locations;
- Monthly and seasonal distributions of speed limit violations and collisions;
- Program operating costs and revenue generation.

The original enforcement site pool will be updated yearly, based on the long-term evaluation. A comparison between the geographic distribution of sites currently in the pool and city-wide collisions and speed limit violations over the past year may identify new roadway locations for inclusion in the site pool. Special concern (SC) sites can be added to the site pool whenever required. Sites experiencing a continually significant reduction in both collisions and speed limit violations can be removed. The remainder of the sites in the pool can be retained.

4. Test application and simulation

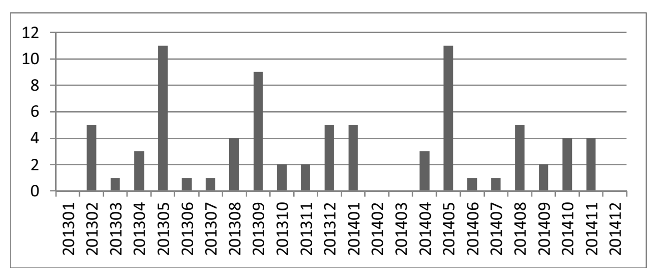
This section presents an application of the monthly MPRE program design methodology introduced in the previous section, based on collisions, speed violations, roadway geometry, various traffic counts, and MPRE operations data provided by the CoE and the Office of Traffic Safety (OTS). Data is first gathered and assessed, and one month is chosen for application of the program design procedure. Then, short-term program performance evaluation results are presented and compared against historical program performance.

4.1. Description of data

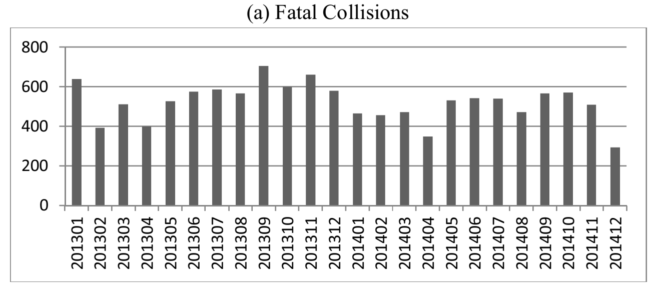
Datasets on roadway information, collisions, and MPRE program deployment details were obtained for use in this example application.

The roadway information dataset contains geographic information on the locations of arterial and collector segments within the City of Edmonton. The basic definition of a roadway segment – on which enforcement sites are based – is that it occurs between two adjacent intersections. However, arterial segments are bookended by fully signalized intersections only (therefore, a segment may include several unsignalized intersections and pedestrian signals), while collector segments are demarcated by intersections with arterial or collector roads only (and not local roads). Arterials typically have two or more travel lanes in each direction, while collector and local roads typically have one per direction and often with parking on each side. A total of 2476 segments were defined within the City of Edmonton. The average lengths of active PR sites in the CoE for arterial, collector and local segments are 3160 ft (963 m), 2326 ft (709 m), and 1882 ft (574 m), respectively (Li, 2014).

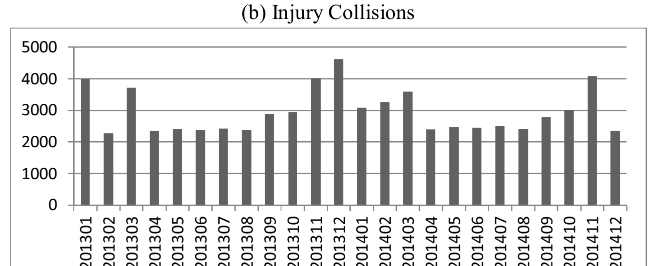
Collision data from 2013 through 2014 were initially assessed for this sample application. The dataset contains the location, date,



(a) Fatal Collisions



(b) Injury Collisions



(c) Property-Damage Only (PDO) Collisions

Fig. 3. Monthly Collision Data on Arterial and Collector Segments (2013 & 2014).

and severity recorded for 83,594 collisions. Of these, 80 were fatal, 12,514 were injury, and 71,000 were property-damage only collisions. Fatal, injury, and PDO collision counts by month are presented in Fig. 3.

According to Fig. 3a, the months of May 2013 and May 2014 experienced the highest numbers of fatal collisions, at 11 each. The second highest count of fatal collisions was seen in September 2013. In terms of injury collisions (Fig. 3b), September 2013 saw the highest number, at 707. More property-damage only (PDO) collisions are likely to occur during the winter months than other months of the year (Fig. 3c), as there can be significant snowfall in Edmonton between November-March.

Deployment data from January 2013 through February 2015 were also obtained. The dataset contains operator ID, site ID, date, start time, end time, number of violations, number of tickets, and vehicle count for each site visit made. Some additional cleaning and processing was required to prepare this dataset for use. Basic descriptive statistics of the final deployment dataset used in this application are presented in Table 1.

Table 1 shows that over the course of 26 months, over 23,000 enforcement site visits were made to 232 enforcement sites. The table also shows descriptive statistics for the duration, vehicle speeds, violations, tickets, and traffic counts per visit made. The duration of site visits range widely, although on average operators spent over three hours per site visit. The minimum duration of 2 min is one where an operator may have set up equipment and then were called away immediately. A site may even be visited for the entire duration of a shift (10 h). The average number of violations per visit is 27, but can range from 0 up to 353 violations. Of course these values depend on many things including visit duration, traffic, location characteristics and time of day. Tickets do not necessarily equal violations due to license plate photos being obscured at times. The distributions of both violations and tickets are heavily right skewed.

Based on the collisions and deployment data, a month that is considered to be as “typical” or “average” as possible was sought for application of the MPRE program design methodology. This month was determined to be May 2014. May 2014 experienced 530 injury collisions, and 895 enforcement site visits at 105 enforced sites. The 2013–2014 average number of injury collisions is 521, with 891 enforcement site visits at 107 sites. As a result the program methodology was applied to May 2014, with sites for enforcement attention were identified and scheduled (as per Sections 3.2 and 3.3, respectively) based on prior data from January 2013 to April 2014. The performance evaluation results were assessed and compared against historical deployment results from May 2014.

Table 1
Deployment Data Descriptive Statistics (January 2013–February 2015).

Total sites (segments) visited[a]	232
Arterial sites	129
Collector sites	103
Total number of site visits	23166
AM shift	12500
PM shift	10666

Per visit:	Mean	Std. Dev.	Min	Median	Max
Duration (min)	204	96.6	2	197	614
Speed (km/h)	52	11.0	30	50	100
Violations	27	29.6	0	16	353
Tickets	22	25.9	0	13	314
Traffic Count	1289	1061.2	1	1007	8097

[a] Local roads were excluded in this table, and their *UI* values not calculated, because only a very small number of local sites were enforced. Additionally, as mentioned in Section 3.2, very few collisions occurred on local roadways, with no injury or fatal collisions reported.

4.2. MPRE program framework application

The program is applied to the month of May 2014. The following steps were taken based on the data introduced in Section 4.1. For this application, only photo radar (PR) sites on arterial roads and collector roads were considered, thereby excluding PR sites on local roads, as well as speed survey (SS) and special concern (SC) sites. The reasons for this were as follows: first, PR sites on local roads had consistently low *PI* values and would not have made it onto the monthly site list anyway. Second, it was decided that an application limited to PR sites (excluding SS and SC sites) would provide a sufficiently informative demonstration of the proposed program.

4.2.1. Site identification

There are three steps involved with calculating indices for all photo radar (PR) sites.

4.2.1.1. Normalize midblock collision and speed limit violation data. The collision and speed violation data were normalized for PR sites by road type. Only when a vehicle’s speed exceeds the speed limit at a pre-determined tolerance will the photo radar system be triggered, and the speeding behavior be identified as a violation. Violations were captured during enforcement, and the enforcement time varied from site to site. Therefore, it is reasonable to use the average number of violations per hour rather than the total number of violations. The data used to normalize collisions and speed violations is a subset of that which is displayed in Fig. 2 and Table 1, respectively, from May 2013–April 2014. Because May 2014 was chosen for analysis, realistically, collisions and MPRE deployment data only up to April 2014 would have been available for use in determining *PI* values. In addition, although data is available from January 2013 onwards, the OTS took over management of the MPRE program in April 2013, and it was decided to use data only from that point forward. It was suggested in Section 3 that *PI* values ought to be computed based on collision and violations data from the previous 12 months; as a result, a subset of the data described in 4.1 (from May 2013 through April 2014) were used. The values calculated from this subset are not unexpected nor do they differ greatly from those of Fig. 3 and Table 1; as a result, they are not shown here in the interest of brevity.

4.2.1.2. Compute urgency index (UI) and priority index (PI) for each site. As explained previously, for PR sites, the Priority Index equals the Urgency Index ($PI = UI$). The coefficients on collisions at different severity levels ($\alpha_F, \alpha_I, \alpha_P$) were calculated based on direct collision costs taken from a 2007 collision cost study of the Edmonton Capital Region (De Leur, 2010). The probabilities of an injury collision and a fatal collision resulting from excessive speed, required to calculate the speed violation coefficient (β), were taken from a Spanish study (Ayuso et al., 2010).

Table 2 shows the values used to calculate the collision and speed violation coefficients according to Eqs. (3) through (7).

4.2.2. Enforcement resource scheduling

4.2.2.1. Monthly site list. In the CoE’s current MPRE program, two 10-h enforcement shifts are scheduled each day of the week (from 6AM–4PM and 4PM–2AM), with one squad assigned for MPRE in each shift. There are four squads in total, each of which has up to nine enforcement units (vehicle + device) and operators. Program standards dictate that each operator is expected to visit a minimum of two sites per shift (Wang et al., 2014). Assuming there are 30 days in a month and all enforcement resources are deployable, about 1080 site visits can be made in one month.

Table 2
Calculating collision and speed violation coefficients.

	Direct cost per collision (CAD)	Probability of collision resulting from speeding	Coefficient value
Fatal collision(α_F)	181,335	0.87	16.6
Injury collision (α_I)	39,524	0.13	3.6
PDO collision (α_P)	10.902	n/a	1.0
Speed violation (β)	n/a	n/a	5.3

Historical data from the CoE indicates that an active MPRE site is visited about 9–10 times per month on average (Li, 2014); therefore, a minimum of 108–120 sites should be included in a monthly site list for CoE. This number is likely to be different in another jurisdiction.

Accordingly, 108 sites were enforced during the month of May 2014. Therefore it was initially decided that the month site list would have 108 sites. However, once sites were assigned Priority Indices (*PIs*) and then ranked by their *PI* values using the method of Section 3.2, it was found that the *PI* values of sites ranked 109th and 110th (2.11 and 2.10, respectively) were very close to that of the 108th ranked site (2.13). Therefore, the top 110 sites were selected for the list. Table 3 contains a summary of the site list. It gives the number of sites in each level, and the highest and lowest *PI* values of the sites contained in the level.

This site list is used to assign site visit frequencies and set the weekly job lists.

4.2.2.2. Weekly job lists & squad deployment schedules. There are a total of four squads in the CoE MPRE program; a squad will work four days on and then have four days off. Therefore, at any given time there are two squads working, with one of these squads responsible for shift 1 (6AM–4PM) and the other for shift 2 (4PM–2AM). One squad cannot be assigned to both shifts, as an operator that works for 10 h is required to take off at least eight hours before their following shift.

The weekly job lists for May 2014 are created according to historical deployment data from the CoE MPRE program from April 2014, and the staffing resources and regulations described above. The data indicates that on average, 2–3 sites are visited by an operator during a single shift. For this test application it will be assumed that operators will visit 2 sites per shift. Therefore, if there are 31 days in May, 992 site visits can be scheduled for the month (31 days $\times$ 2 shifts/day $\times$ 1 squad/shift $\times$ 8 operators/squad $\times$ 2 site visits/operator = 992 visits). As stated in Section 3.3.2, each site is randomly assigned a number of visits within the range of the level in which it falls. The total number of visits should, of course, not exceed 992. Table 4 displays the number of visits assigned to each site in the May 2014 site list.

The median number of visits per site for all sites is 7. Certainly this value ranges greatly between the three levels shown above, with the Level 1 sites receiving a median of 5 visits over the month and Level 3 sites receiving 28.

In a real-life MPRE program application, the information in Table 4 would be used by program managers to create a weekly job list as per Section 3.3.2. Then, squad leaders would take these weekly job lists and distribute the site visits to their operators. The operators would then plan out their visit schedule using some of the guidance materials provided (Section 3.3.3). Program managers and squad leaders perform these tasks based on their past experiences, ground knowledge, and intuition. Given that this is a test application, the authors simulated both these sets of tasks according to the instructions set forth in Sections 3.3.2 and 3.3.3, based on lengthy discussions and meetings with current MPRE program operators in the CoE. Table 5 shows an 11-day sample of how the four squads (S1–S4) were scheduled for the month. Recall that for each shift, squad operators will visit two sites each.

Table 3
Summary of sites in May 2014 site list.

Level	Importance	Number of sites	*PI* values	
			Highest	Lowest
3	High	7	23.53	9.12
2	Medium	29	6.32	4.02
1	Low	74	3.98	2.1
	Total:	110		

Table 4
Randomly assigned MPRE visits by site level.

Level	Importance	Number of sites	Visits			
			Min	Median	Max	Total
3	High	7	22	28	35	190
2	Medium	29	12	14	20	433
1	Low	74	1	5	11	369
	All	110	1	7	35	992

The schedule is generated to abide by the operator scheduling regulations described previously, and the principles listed in Section 3.3.3. These principles are that operators in one shift should be geographically distributed throughout the city, a site is only visited once per shift, a site should not be visited in two sequential shifts, and the two sites visited by an operator within a shift should be relatively close to one another to avoid unnecessary travel. The process by which program managers might assign site visits to certain weeks would largely be dictated by intuition and previous experience; as a result, for this test application, each site visit was randomly assigned an index indicating a week and a shift (1 or 2). In emulating the site visit assignments to operators by the squad leaders, the visits were allocated taking into account the sites' importance levels (Levels 1–3) and geographic locations. Clearly, the squad leaders' previous experiences would also dictate how the assignment is performed.

In a real-life application, program managers may find that it is appropriate and optimal to schedule certain squads only in Shifts 1 or 2, and certain squad leaders may know to assign certain operators within their squad to sites in certain parts of the city or types of sites, etc.

4.3. Candidate (short-term) evaluation measures

The site selection and scheduling results described in Sections 4.1 and 4.2 were evaluated against the actual May 2014 MPRE program results, using several measures, including the following: total distances travelled between site visits made by an operator (*TTD*), total *PI* for all sites visited (*TPI*), and violation coverage (*VC*). These measures may be used for the short-term evaluation discussed in Section 3.4.1.

4.3.1. Total distance traveled between sites (*TTD*)

The distance traveled between sites visited within a shift by an operator is a measure of efficiency. Currently, operators do not

Table 5
Weekly squad schedule (with assigned site IDs).

DATE	SQUAD	SHIFT	Operator 1		Operator 2		Operator 3		Operator 4		Operator 5		Operator 6		Operator 7		Operator 8	
			Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2	Site 1	Site 2
May-01	S1	AM	10469	20543	11120	10401	10831	10918	20161	11003	10612	10754	21122	21115	21203	10656	10779	10794
	S2	PM	10936	10997	10357	21336	10918	10910	10563	10738	10527	10040	21209	21206	10093	10866	20510	10693
May-02	S1	AM	10469	20543	20817	20204	10723	10307	10046	10048	10768	10754	10527	10253	10655	10656	10079	10699
	S2	PM	10936	10997	11120	10141	10298	20643	10214	11003	10263	10754	21122	21115	11057	10866	21112	10571
May-03	S1	AM	20793	20132	11120	10797	10918	10910	10612	10048	10527	10040	10023	10522	10093	10866	20510	10693
	S2	PM	10469	10232	20191	10928	10723	10299	10214	11003	10768	10754	21209	21206	21203	10656	10866	10079
May-04	S1	AM	10469	10655	11120	20988	10227	10536	10207	10738	10768	10754	10524	10522	10655	10656	10078	10699
	S2	PM	20129	20132	10926	10928	10298	20643	20161	11003	10527	10045	21211	21210	10131	10866	21422	21420
May-05	S3	AM	10831	20141	11120	10399	10723	10299	10046	10048	10612	10754	10527	10253	10093	10866	21112	10571
	S4	PM	10469	21135	10926	10928	10918	10910	10214	11003	10527	10040	21209	21206	10655	10656	10866	10689
May-06	S3	AM	10831	10386	11120	10797	10505	20204	10612	10048	10768	10754	21211	21210	21203	10656	10078	10699
	S4	PM	10469	20543	20191	20189	10331	20643	10214	10208	10768	10754	10563	10253	10851	21259	10779	10693
May-07	S3	AM	10831	21429	10926	10928	10298	10299	10214	11003	10527	10040	21209	21206	10851	21259	10078	10699
	S4	PM	20643	10902	11120	10141	10331	20643	10207	10738	10768	10754	21122	21115	10655	10656	20510	10693
May-08	S3	AM	10469	21135	10357	21336	10298	10900	10214	11003	10768	10754	20287	10522	21209	21206	10866	10689
	S4	PM	21419	21420	11120	20988	10723	10299	10058	10738	10527	10040	21211	21210	10655	10656	10078	10699
May-09	S2	AM	10831	21429	11120	10399	10918	10720	20161	11003	10527	10045	10574	10522	10661	10656	21112	10571
	S1	PM	10469	20543	20817	20204	10331	20643	10058	10738	10768	10754	21116	21210	10851	21259	10866	10689
May-10	S2	AM	10936	10997	10926	10928	10298	10299	10214	11003	10263	10754	21209	21206	10661	21259	10078	10699
	S1	PM	10469	20543	11120	10401	10505	20204	10046	10048	10527	10040	20287	10522	10655	10656	21112	10571
⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮	⋮
May-31	S4	AM	10936	21419	11120	20988	10723	10299	10612	10753	10527	10253	21116	21210	10661	10656	10025	10026
	S3	PM	10469	10655	10357	21336	10918	10910	10227	20160	10263	10754	10571	10522	21209	10645	20510	10794

explicitly consider the distances between the sites they visit over the course of a shift, although operators will tend to visit clusters of sites located in some proximity to one another. As mentioned in Section 3.3.3, the site visit schedule planning guidance materials could be provided in a geographic format such that operators are able to plan site visits based on sites' relative proximity to one another. The total distance traveled is calculated for all distances between two sites visited by operators in each shift over the course of the month. It excludes distances traveled between sites and their dispatching office.

$$TTD = \sum_{s=1}^{S}\sum_{p}^{P_s} D_p \tag{9}$$

where:

TTD = total distance traveled;

D_p = distance travelled by operator p in shift s between sites 1 and 2;

P_s = total number of operators dispatched in shift s, and

S = total number of shifts in the month.

4.3.2. Total priority index (TPI)

The total priority index (TPI) is the sum of the priority indices of all site visits made. It is a measure of how well and how much the MPRE program is covering sites with enforcement needs.

$$TPI = \sum_{i=1}^{I} PI_i F_i \tag{10}$$

Where:

TPI = total priority index;

F_i = total monthly deployment frequency at site i;

PI_i = priority index of site i, and

I = total number of sites enforced in the month.

4.3.3. Total violation coverage (VC)

This performance measure is an indication of how the program is performing in terms of catching speed violators, which in turn indicates the program's efforts for law enforcement and traffic safety. Given that this is a test application, no actual violations results were captured. As a result, in the absence of data, it was assumed that the hourly speed violation rate at an enforcement site can be approximated by a lognormal distribution, for each of the three levels (low, medium, and high importance). The distributional parameters for the sites of each level, based on the CoE data (described in Section 4.1) from May 2014, are shown in Table 6.

The hourly speed violations at each visited site were simulated by drawing random values from lognormal distributions with the above parameters, based on a site's membership to a level.

4.4. Results

Table 7 contains results of the existing MPRE program deployment from May 2014, the results of the proposed program test application, and the changes in performance between the two. It can be confirmed that the actual enforcement resources deployed in May 2014 (under "shifts"; total shifts, shift hours, average operators per shift) were also used as inputs for the test application, to ensure that the comparison is as fair and balanced as possible.

It can be observed that even with a limit of two site visits per shift, the proposed program would require more site visits and more active enforcement (i.e. the time that operators are actually doing enforcement at each site). Based on analysis of the data from Section 4.1, an expectation for operators to maintain this schedule (on average) appears to be a reasonable one. The total distance

Table 6
Speed violations distribution parameters.

Level	Mean	Standard Deviation
1	20.2	23.10
2	32.9	32.46
3	41. 0	28.89

Table 7
May 2014 results, current versus proposed program.

		Existing program	Proposed program	% change
Shifts	Total number of shifts (May 2014)	62		
	Total shift hours	4960		
	Average number of operators per shift	8		
Site visits	Total number of sites enforced	107	110	3%
	Total site visits	895	992	11%
	Total active enforcement hours	3,224	3,968	23%
	Average active enforcement hours per operator per shift	6.5	8	23%
	Total distance traveled (*TTD*), km	13,993	12,892	−8%
PI	Total *PI* (*TPI*)	371	460	24%
	Average *PI* per enforced site	3.47	4.19	21%
Violations	Total violations	32,425	43,134	33%
	Average violations per operator per shift	65	87	33%
	Average violations per site visit	36	43	19%

traveled between sites in a shift is 8% lower in the proposed program. This suggests that operators should be able to reduce their travel if it is made an explicit goal of the program and if they are given the appropriate tools to achieve this (i.e. mapped site visit planning guidance).

Given that the proposed program uses priority indices *PI*s to focus more enforcement resources to sites with higher *PI* values, the 24% increase in total *PI* coverage between existing and proposed programs is within expectations. Even with the (very small) increase in number of sites enforced with the proposed program (from 107 to 110) and the larger increase in site visits (from 895 to 992), the average *PI* per enforced site increased 21%. Note also that the site *PI*s (total and average) are independent of the time spent at each site. The most significant result is the increase in the total violations that are expected to be captured with the proposed program, at 33%. Each operator could expect to capture 22 more speed violators on average per shift (33% increase), and 7 more violators per site visit (19%). The reason for the latter figures showing a smaller increase is due to the fact that more site visits are made over the course of the month in the proposed program. However, recall that the speed violations resulting from the proposed program were estimated based on random draws from an assumed lognormal distribution of violations, and these results are entirely dependent on these assumptions.

Overall, it appears that the CoE MPRE program could expect some sizeable gains in efficiency, violation coverage, and coverage of sites with safety issues (as represented by *PI* values) with implementation of the proposed program. It should be noted here that Table 7 presents a short-term rather than long-term evaluation. A long-term evaluation would have been preferred; the best measure of program efficacy is collision reduction, given that the overall goal of the MPRE program is to reduce collisions. However, as this was a test evaluation where outcomes were estimated, it is neither appropriate nor accurate to estimate the potential collisions (PDO, injury, or fatal) resulting from this program implementation.

5. Conclusions and future steps

Systematic, data-driven procedures that guide deployment for mobile photo radar enforcement (MPRE) programs have received little attention in the literature, and this paper aims to address this gap. A new MPRE program procedure is proposed in order to improve the utilization of limited enforcement resources, increase efficiency and contact with problematic roadway locations, and ultimately, improve urban traffic safety. The proposed site selection, prioritization, enforcement scheduling, evaluation, and adjustment process is an evidence-based program design, incorporating updated program performance information and traffic and enforcement data to achieve well-defined goals. The proposed program seeks to generate MPRE deployment plans on a monthly basis, with evaluations performed monthly as well as long-term. First, roadway sites that are potential targets for MPRE attention are identified through a selection and prioritization process informed by speed limit violation and collision data. Then, information regarding MPRE program resource availability is used to determine which sites are to be enforced, and how much, on a month-to-month basis. Finally, the resulting site visits are distributed on a weekly basis, while observing some basic rules (i.e. sites may not be visited in sequential shifts, etc.). In keeping with the existing MPRE program cultures, program managers and enforcement personnel (operators) maintain autonomy in making decisions in every step of the process. This process and its results are evaluated on both a short-term and long-term basis. The monthly evaluation is to facilitate monthly site list and deployment instruction adjustments, consisting of deployment statistics and traffic data as changes to collisions cannot be evaluated on such a short timeframe. The long-term evaluation is for assessing changes in collisions and speeds, to in turn assess overall program efficacy in improving urban traffic safety, and inform larger program changes as needed.

Using historical data from the CoE, the proposed program was applied to simulate a deployment plan for one month. May 2014 was chosen as it was found to be a very typical month in terms of MPRE deployment and traffic characteristics. Resource availabilities from May 2014 were used as inputs to generate weekly site visit plans for the month. The results of program application were assessed against the results of the existing MPRE program in place in May 2014, using several candidate short-term evaluation measures. Based on the results, it is expected that with implementation of the proposed program, the CoE's MPRE program may observe moderate to high improvements in travel distance efficiency and coverage of sites with safety issues. Specifically, the test application results in an 8% reduction in travel distances, 24% increase in *PI* coverage, and an estimated 33% increase in speed violations capture.

The promising test results aim towards the next step—a real-life, full-scale trial deployment of the proposed program. In fact, the entire long-term evaluation feedback and program redesign process can only be developed, applied, and assessed through a full-scale deployment given the data-driven nature of the proposed program. Full-scale deployment would allow for more conclusive documentation of the potential gains in efficiency and coverage over the short- and long-term. Traffic safety benefits, including the strengths of the relationships between indicators and proxies, can be only assessed over the long-term. Therefore, it is recommended that next steps do include a pilot program deployment, particularly in a jurisdiction where an on-going MPRE program is in place such that the results of the new program can be compared to those of the existing. It is also recommended that feedback about the program be gathered from program managers, squad leaders, operators, and other program facilitators. This proposed program is expected to be deployed within the City of Edmonton in the near future. Additionally, MPRE programs should be conducted in tandem with education and awareness campaigns, in order to enhance program benefits through the general deterrence effects these campaigns promote amongst the driver population.

This proposed MPRE program design framework can provide planners, engineers, and law enforcement professionals with a systematic, analytic, and data-driven process by which to design, deploy, and operate a MPRE program. The design framework was built in response to the needs of the City of Edmonton's current MPRE program. However, its development was generalized for adaptation and adoption within any urban jurisdiction looking to begin a new program, or make improvements to an existing one, in their pursuit of greater traffic safety.

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