Scheduling and Deployment Strategies for Mobile Photo Radar Enforcement

by

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ABSTRACT

Speeding is a leading cause of urban collisions and often causes injury and death. Consequently, photo enforcement has been globally adopted as a countermeasure in speed management and has been proved to be effective in mitigating speeding problems. Although there is extensive research pertaining to photo enforcement, there is a critical research gap regarding the development of an integrated deployment, scheduling, and evaluation process for Mobile Photo Radar Enforcement (MPRE). As a result, the objective of this thesis is to develop a framework for the MPRE program, aiming to provide planners and schedulers with a systematic and analysis-based procedure to design the MPRE program and schedule enforcement activities. The thesis used the City of Edmonton's (CoE) current MPRE program as the basis to showcase the proposed framework.

The literature relating to the theoretical basis of enforcement, the assessment of MPRE's effects, and the deployment strategies of MPRE used in other jurisdictions was reviewed; information about the current MPRE program in the CoE was consolidated; and the historical data were collected and analyzed. Based on the collected information, a program framework was proposed, which factored in local program needs and institutional characteristics. The framework consists of three parts: a multi-variable site identification and priority-base site selection process for screening potential MPRE locations, the scheduling method for deployment of MPRE, and guidelines for program evaluation and adjustment. The framework was illustrated and tested using a numerical example. The performances of different scheduling methods proposed in the thesis were compared. Although the program framework is designed for the CoE, the systematic procedure and methodologies can be applied to MPRE programs in other jurisdictions.

PREFACE

This research is collaboration with the Office of Traffic Safety (OTS) to improve the Mobile Photo Radar Enforcement Program in the city of Edmonton, Alberta. Some of the contents in this thesis have been included in project reports submitted to the OTS.

Parts of the literature review in Chapter 2 were documented in the first and the second project report, “The Relationship between Photo Enforcement Measures and Roadway Traffic Safety”(Wang, Kim, & El-Basyouny, 2013) and “Review of the Mobile Photo Enforcement Deployment Strategy” (Wang, Barua, Li, Kim, & El-Basyouny, 2013). Contents in Chapter 3 and Chapter 4 were included in the third project report, “Initialization Plan of the Deployment of the Mobile Photo Radar Enforcement in the City of Edmonton” (Wang, Kim, & El-Basyouny, 2014a). The methodologies used for developing the program framework proposed in Chapter 4 have been included in the paper “Development of a Program Framework for Mobile Photo Radar Enforcement” (Wang, Kim, & El-Basyouny, 2014b), which is currently under review for publication.

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LIST OF ABBREVIATIONS

AHP	analytic hierarchy process
CoE	City of Edmonton
CV	community van
DE	directed enforcement
DSM	deterministic scheduling method
EPS	Edmonton Police Service
GIS	geographical information system
ISD	intersection safety device
KDE	kernel density estimation
MPRE	mobile photo radar enforcement
NCD	network centric deterrence
OTS	Office of Traffic Safety
PDO	property damage only
PETS	photo enforcement ticketing system
PI	priority index
PL	photo laser
PR	photo radar
RSM	randomized scheduling method
SC	special consideration
SI	special requirement index
SS	speed survey
UI	urgency index

CHAPTER 1. INTRODUCTION

1.1 Background

Road safety, which directly influences the sustainable development of society and quality of life, is a topic that has attracted much attention and effort from government, industry, as well as the whole society. However, many factors, including unsafe driving behaviour, poor roadway design, and low-quality infrastructures have negative effects on traffic safety, contributing to the occurrence of traffic casualties. Traffic casualties persist as a critical public safety concern and societal problem in almost every country and jurisdiction in the world today. According to statistics on the global status of road safety, more than one million people lose their lives every year in traffic incidents, resulting in several billions of dollars' worth in economic loss (Jacobs, Aeron-Thomas, & Astrop , 2000). Although the number of traffic fatalities worldwide dropped to 1.24 million in 2010, from 1.26 million in 2000, it remains at an unacceptably high total, which is estimated to be the eighth leading cause of death globally (World Health Organization, 2013). Non-fatal injuries resulting from traffic collisions remain at an even higher level, ranging from 20 to 50 million cases per year (World Health Organization, 2013). In Canada, an optimistic downward trend was observed with a drop of 10.3% from 2010 to 2011, for both fatalities and injuries. Despite this drop, there were still 2,006 fatalities and 10,443 serious injuries in 2011 (Transport Canada, 2011). In Alberta, 139,179 collisions occurred in 2011, among which 313 people were killed and 18,584 people were injured (Alberta Government, 2013). As for the City of Edmonton (CoE), 26 fatal collisions (18.2% increase from 2011) were recorded in 2012, while the number of injury collisions was 3,362 (3.4% decrease from 2011) in the same year (Office of Traffic Safety, 2013). Without taking urgent action to reduce current incident levels, traffic incidents are predicted to be the fifth leading cause of death by 2030 (World Health Organization, 2013).

Among different factors contributing to road collisions, speeding is one of the most prevalent factors and deserves major attention. Higher speed increases the likelihood of road injuries and the severity of road collisions (Nilsson, 2004). In Canada, 27% of fatal collisions and 19% of severe injuries involved speeding (Transport Canada, 2011). In Alberta, 46.1% of fatal collisions and 42.8% of non-fatal injury collisions resulted from improper actions relating to speeding (Alberta Transportation, 2012), In CoE, 23,237 collisions occurred in 2012, and more than half of them (13,207) were related to speeding (Office of Traffic Safety, 2013).

Three countermeasures are widely used to address speeding: engineering, education, and enforcement. Driving environments can be improved by creating reasonable geometric designs, constructing high-quality transportation infrastructures, and installing appropriate traffic control devices. In addition to improving roadway infrastructure, educational programs and massive media campaigns are also helpful in increasing the public's awareness of the importance of abiding by traffic laws voluntarily (European Transport Safety Council, 2011). However, even if drivers realize the serious consequences of inappropriate driving behaviour such as speeding, sometimes road users cannot help violating traffic rules for a specific purpose, such as driving at a high speed to reduce travel time. Therefore, in addition to depending on road user's subjective awareness of complying with traffic regulations, enforcement, which provides an external restraint, is required to help road users regulate their behaviour and increase their compliance to traffic laws.

Conventional traffic enforcement, which is labour-intensive, has been used as the primary enforcement method and has achieved ideal effects in reducing traffic injuries and fatalities

(Kallberg, Zaidel, Vaa, Malenstein, Siren, & Gaitanidou, 2008). According to the results of a European study, due to police enforcement, 680,000 injuries were prevented and 14,000 lives were saved, corresponding to a 35% reduction in the number of fatalities in the 15 member states of the European Union (European Commission, 2007). However, the effects of traditional traffic enforcement are often weakened by the limitation of available manpower and the shortage of solid evidence-based violation judgment due to various subjective elements involved. Traditional enforcement, especially when carried out in urban areas, also exposes police officers to dangerous conditions when chasing violation vehicles in a high-density area at high speeds (South, Harrison, Portans, & King, 1988). Photo enforcement, an advanced enforcement method that introduces the use of photo radar (PR) or photo laser (PL) into conventional physical policing enforcement, has become a powerful and widely used method in many countries, including Canada, the Unites States, the United Kingdom, France, Germany, Australia, China, Korea, and others (Retting, Farmer, & McCartt, 2008).

Previous studies have demonstrated that mobile photo radar enforcement (MPRE) can reduce mean vehicle speeds by 2–14% (Goldenbeld & Schagen, 2005; Cities of Beaverton and Portland, 1997; Berkuti & Osbuen, 1998; Retting & Farmer, 2003). The percentage of speeding vehicles was reduced from 23% to 2.9% in Victoria, Australia; in San Jose, California, MPRE resulted in a 15% reduction in the number of drivers speeding at 10 mph over the speed limit (Coleman & Paniati, 1995; Davis, 2001). Many studies have found that MPRE is also effective in reducing serious collisions that result in injuries and fatalities (Diamantopoulou & Cameron, 2002; Vaa, 1997). Because PR enforcement has shown positive effects, it is highly supported by the public. According to a survey conducted in Canada in 2007, 69% of respondents supported the placement of speed cameras on highways to address the speeding problem, while 77%

approved of PR enforcement at intersections to capture red light or speeding offences (Canada Safety Council, 2007). Similar public support has been recorded in Europe. Among 23 European countries, 66% of citizens were in favour of PR enforcement, and 76% of the interviewees even supported intensifying PR enforcement efforts (SafetyNet, 2009).

In Alberta, the Traffic Safety Plan was introduced in 2007, with the aim to reduce the number of fatalities and serious injuries in speed-related collisions by 20% province-wide by 2015. Implementing an effective speed management program has been identified as one of the top road safety priorities for Alberta. Automatic enforcement is one of the core strategies used in speed management (Alberta Transportation, 2006). To support the Alberta Traffic Safety Plan, a speed management program was proposed in Edmonton. The Speed Management Committee was established in late 2010 to support the implementation of the speed enforcement program. The committee consists of the Office of Traffic Safety (OTS), the Edmonton Police Service (EPS), the Engineering Office of the Transportation Services Department of the CoE, the CoE Capital Construction Department, and the Edmonton Federation of Community Leagues. Road safety was planned to be improved mainly by enhancing education, engineering, enforcement, and evaluation, aiming at attaining the following targets:

- Reduce the number of intersection-related collisions by 20%;
- Increase and maintain the belt-wearing rate at 95%;
- Reduce accidents caused by impaired driving;
- Reduce speed-related collisions (Shimko & Walbaum, 2010; Alberta Transportation, 2006).

As for enforcement technologies currently used in Edmonton, both automatic and manned speed enforcement have been adapted to control speeding (Wang, Barua, Li, Kim, & El-Basyouny, 2013).

Photo radar (PR) is an advanced technology adopted by the CoE in speed enforcement activities. Some equipment is fully automatic, such as intersection safety devices (ISD). Others need the involvement of manpower, such as MPRE. The first time that photo radar enforcement was applied in Edmonton dates back to 1993, but it was not until April 2012 that the OTS took over the job of managing the PR program (Wang, Kim, & El-Basyouny, 2014a).

As requested by OTS, the performance of the MPRE program in the CoE needs to be reviewed. The scheduling and deployment strategies of the current MPRE program need to be systematically redesigned in order to maximize the utilization of enforcement resources and deployment efficiency. Considering the program has been running for years and the enforcement culture has already formed, improving the program by incorporating the program-specified characteristics and without disrupting the current culture unduly is a major challenge for the research.

1.2 Research Objectives

A review of both the academic literature and state-of-the-practice on various topics related to MPRE reveals that extensive studies have documented the procedures, methodologies, and performance measures used for evaluating MPRE programs; however, there is little information about the systematic design process for initializing or improving MPRE programs.

To fill this research gap in the literature and provide a systematically designed process of scheduling, as well as a set of deployment strategies to support the improvement of the MPRE program used by the CoE, this thesis aims to achieve the following objectives:

- Review the regulations, deployment patterns, and enforcement results of the MPRE program in the CoE

- Develop a quantified method for enforcement location identification and selection

- Develop an improved scheduling method that increases the coverage of high-risk locations, enhances the subjective and objective risk (general deterrence and specific deterrence) of detection and punishment, and incorporates the current culture of Edmonton's MPRE program

Eventually, it is aimed at increasing speed compliance and reducing road collisions so as to improve the efficiency and efficacy of MPRE, and consequently, city-wide traffic safety.

1.3 Thesis Structure

The remaining contents of the thesis are organized into five chapters.

Chapter 2 gives the literature review results of both the best practice and researches relating to MPRE. The enforcement theory and mechanism as well as the relationship between enforcement, speed, and traffic safety are reviewed. The deployment strategies adopted by the MPRE programs in other jurisdictions are summarized in this chapter.

Chapter 3 introduces the enforcement equipment availability, staffing level and current deployment strategy of the MPRE program in the CoE. This research is designed based on the local data of the MPRE program in the CoE. The data assessment, collection, and processing work are described. The preliminary data analysis results are listed at the end of this chapter.

Chapter 4 presents the framework of the program design, the methodologies for site identification and selection, and the scheduling and deployment strategy developed for the MPRE program in the CoE.

Chapter 5 provides a numerical example to demonstrate the program framework. The performance of the randomized scheduling method is compared with that of a deterministic scheduling method.

Chapter 6 summarizes the work, contributions and limitations of this research. The improvements and future work are also suggested at the end of this chapter.

CHAPTER 2. LITERATURE REVIEW

This chapter presents the literature review results of both research and best practices related to photo enforcement. Understanding the enforcement mechanism and relationship between photo enforcement and road safety is helpful in outlining the framework for program design. The site selection method and deployment strategies used by other jurisdictions are valuable references for this research. This chapter also identifies the research gaps, and some of the contents in this chapter have been documented in the first and second report of the optimization of mobile photo radar enforcement (MPRE) program in the City of Edmonton (Wang, Kim, & El-Basyouny, 2013; Wang, Barua, Li, Kim, & El-Basyouny, 2013).

2.1 Traffic Enforcement Theory and Mechanism

2.1.1 Enforcement Theory

Traffic enforcement theory is derived from eighteenth-century classical deterrence theory (Zaal, 1994). Generally, rational people tend to comply with traffic rules to avoid punishment for non-compliance. Traffic enforcement aims to affect road users' behaviours by exposing them to the risk of being caught and punished for violating traffic rules. As a result, it is expected that compliance to traffic rules will increase and the possibility of collision occurrence will decrease as well. Traffic enforcement tends to influence road user's behaviour through two processes: general deterrence and specific deterrence (Zaal, 1994; Mäkinen, et al., 2003; Tay & Barros, 2009; Tay & Barros, 2011)

The threat and legal punishment generated from general deterrence broadly influences the public. Under traffic enforcement, the chances of a violator being caught and punished will increase. Potential violators will not risk offending traffic rules when seeing another individual penalized, thereby increasing compliance to traffic rules (Tay & Barros, 2009; Tay & Barros, 2011). Specific deterrence targets individual perception. After being detected and penalized for violating traffic rules, the road user will refrain from committing another violation due to the fear of being penalized again (Tay & Barros, 2009; Tay & Barros, 2011).

To effectively achieve either general or specific deterrence, a high possibility of being detected and penalized by traffic enforcement as well as a steadfast penalty system should be ensured (Zaal, 1994). Because the effect of general deterrence is more pronounced than the effect of specific deterrence, traffic enforcement should primarily aim at achieving general deterrence by increasing the subjective risk of detection and punishment (Wegman & Goldenbeld, 2006).

2.1.2 Enforcement Mechanism

The mechanism of traffic enforcement is put in effect through subjective and objective risk (Zaal, 1994). The objective risk can be increased by following four principles, including 1) improving enforcement publicity and unpredictability, 2) focusing on high-risk time periods and locations, 3) using a mix of highly and less visible forms of enforcement, and 4) implementing long-term enforcement activity (Wegman & Goldenbeld, 2006). The subjective risk results in general deterrence and consequently increases the effectiveness of traffic enforcement (Zaal, 1994). Increasing subjective risk relies on three basic deterrence principles: 1) certainty (unavoidability of punishment), 2) celerity (immediate punishment), and 3) the severity of punishments (Zaal, 1994; Carnis & Blais, 2013). Therefore, an effective enforcement should create a high possibility of detection and penalty by covering a large area of road network with the constrained resources. Once the violation is recorded, the owner of the speeding vehicle should receive a written notice within a short period of time after the violation occurrence. The punishment should match the severity of risk caused by the violator. It is suggested that the magnitude of the penalty be proportional to the extent of the speeding (Carnis & Blais, 2013).

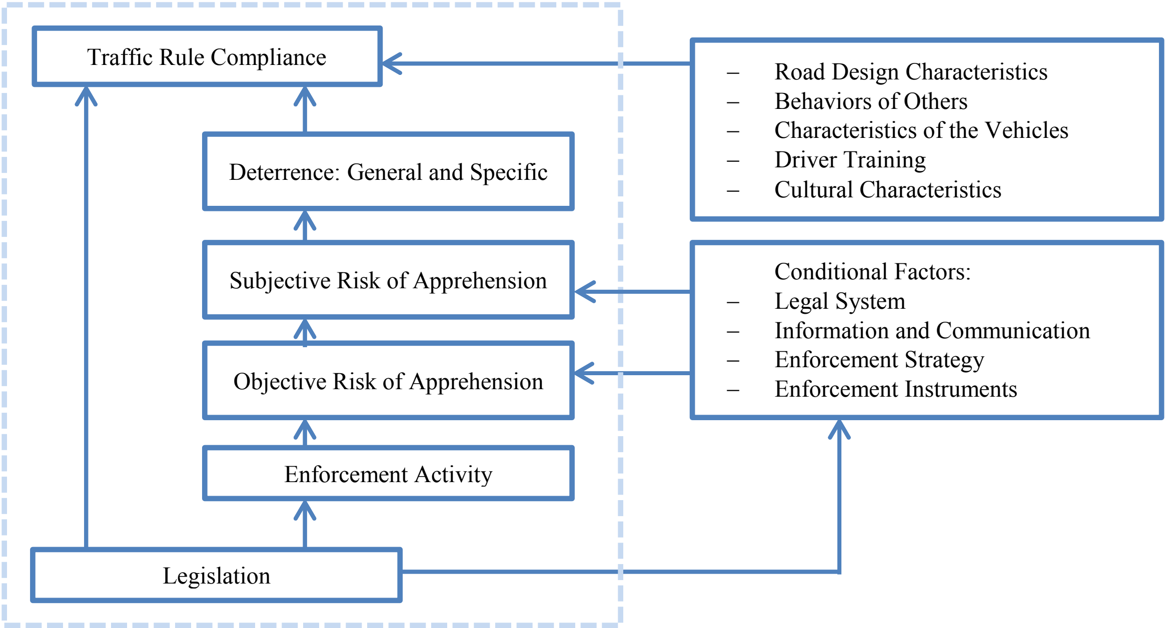


Figure 1 Traffic Enforcement Mechanism (inside dotted frame) and the Influence of External Factors (outside dotted frame) (Wegman & Goldenbeld, 2006; Aarts, Goldenbeld, & Schangen, 2004)

As shown in Figure 1, the traffic enforcement activities result in increases in both objective and subjective risk of apprehension, and thereby enhance general and specific deterrence. The arrow that directly points from “Legislation” to “Traffic Rule Compliance” indicates people who generally abide by traffic rules voluntarily, regardless of the implementation of traffic enforcement. Voluntary compliance can be possibly explained by external factors, such as cultural and road design characteristics.

In summary, with a high certainty of being caught and high severity of punishment for traffic offences, effective and intensified traffic enforcement increases the objective and subjective risks of apprehension. Speeding and speed-related crashes will be reduced due to general and specific deterrence, thereby improving road safety.

2.2 Relationships between Collisions, Speed, Photo Enforcement, and Safety

2.2.1 Relationship between Speed and Safety

As long as drivers travel within the safe speed range, a slight increase in vehicle speed has positive effects on saving travel time and increasing mobility (Box & Bayliss, 2012). However, driving too fast will put both drivers and other road users at risk of danger. Speeding is one of the major threats to road safety. In Canada, 27% of traffic fatalities and 19% of severe injuries in 2011 were due to speeding (Transport Canada, 2011).

Excessive speed refers to when a vehicle travels above the posted speed limit, while inappropriate speed means a vehicle is travelling too fast for the prevailing weather and road conditions, even if its speed is within the speed limit (Robinson & Singh, 2006). Higher speeds are associated with an increase in collision risk (Peden, et al., 2004; Elvik, Christensen, & Amundsen, 2004; Nilsson, 2004). According to the speed power model proposed by Nilsson, the probabilities of an injury collision, a severe injury collision, and a fatal collision are proportional to the square of speed, the cube of speed, and the fourth power of speed respectively (Nilsson, 1982; Nilsson, 2004). For instance, a 5% increase in average speed can lead to a 10% increase in all injuries and a 20% increase in fatalities (Nilsson, 2004). The reasons that a higher speed increases collision risk can be explained with four observations. First, the driver's field of vision reduces at higher speeds. A driver has a field of vision of 100 degrees when driving at 40 km/h; however, the vision field will reduce to 30 degrees when driving at 130 km/h (OECD, 2006). Second, the reduced vision field weakens the driver's ability to deal with potential dangers, so that their reaction time for deciding to stop increases (OECD, 2006). Third, when driving at a very high speed, the braking distance also increases, consequently increasing the likelihood of collision occurrence (Kloeden, McLean, Moore, & Ponte, 1997). Finally, higher speed also increases the degree of collision severity because a larger amount of energy needs to be absorbed during the impact (OECD, 2006).

2.2.2 Effects of Enforcement on Collisions and Speeding Violations

Several studies have evaluated the effects of different types of traffic safety enforcement on speeding and collisions. In this subsection, primarily the effects of photo enforcement will be reviewed.

Many studies found that photo enforcement is effective in reducing serious collisions resulting in injuries and deaths (Gains, Heydecker, Shrewsbury, & Robertson, 2004; Christie, Lyons, Dunstan, & Jones, 2003). In Norway, photo radar enforcement was shown to effectively reduce fatal and injury collisions by 20% on average (Elvik R. , 1997). Moreover, the dose-response relationship proposed by Elvik reveals that the number of injury collisions decreases with an increase in the amount of enforcement (Elvik R. , 2001). Besides the reduction in collisions, photo enforcement also has remarkable influence in controlling speeding. Some studies showed that the mean speed of vehicles can be reduced by 2% to 14% by deploying speed cameras.

More information about the effectiveness of the photo radar/camera enforcement program in different countries and jurisdictions is summarized in Table 1. As shown in Table 1, covert photo enforcement has great effects on reducing collisions at different severity levels. In addition to the decrease in mean speed, compliance to the speed limit is also improved, and the percentage of speeding vehicles is reduced.

Table 1 Summary of Studies Evaluating the Effects of Photo Enforcement

Location	Enforcement Type	Effects	
		Collisions	**Speeding**
France (Carnis & Blais, 2013)	Covert mobile photo radar enforcement	The fatality rate per 100,000 vehicles reduced by 21%, whereas non-fatal traffic injuries in the first month reduced by 26.2%	N/A
Netherlands (Goldenbeld & Schagen, 2005)	Covert mobile photo radar enforcement	21% reduction in injury crashes involving a motor vehicle in rural areas	3.5 km/h decline in mean speed
British Columbia, Canada (Chen, Meckle, & Wilson, 2002)	Covert mobile photo radar enforcement	25% reduction in daytime speed-related crashes	N/A
France (OECD, 2006)	N/A	30% decline in fatal crashes on highways	5 km/h decline in mean speed;
Washington DC, US (Retting & Farmer, 2003)	Covert photo radar enforcement	N/A	14% decline in mean speed; 82% decline in speeding vehicles
San Jose, CA, US (Davis, 2001)	N/A	N/A	15% reduction in proportion of vehicles speeding 10 mph over the limit
National City, CA, US (Berkuti & Osbuen, 1998)	N/A	51% reduction in crashes	10% decline in traffic speeds
Victoria Australia (Coleman & Paniati, 1995)	N/A	22% decline in total crashes; 38% decline in injury crashes	The percent of speeding vehicles reduced from 23% to 2.9%
New South Wales, Australia (Coleman & Paniati, 1995)	N/A	22% decline in serious crashes	N/A

2.2.3 The Role of Photo Enforcement in Improving Road Safety

Compliance due to photo enforcement will contribute to the reduction of both speeding violations and collisions at different severity levels and consequently result in the improvement of traffic safety. The relationship between photo enforcement and road safety is demonstrated in Figure 2. Although the figure is developed to describe all types of enforcement, it is applicable for illustrating the role of photo enforcement in improving road safety.

As shown in Figure 2, the photo enforcement program is based on a well-planned legal and organization framework. Complying with the guidelines and principles outlined in the framework, photo enforcement will be deployed at identified unsafe locations during high-risk hours. The perceived risk of apprehension will encourage the road users to change unsafe driving behaviour that endangers other people. Increased speed compliance leads to a reduction in speeding violations and traffic collisions. As a result, road safety will be improved. Improved traffic safety will reduce the financial costs associated with processing the consequences of violations and collisions, and consequently benefit society.

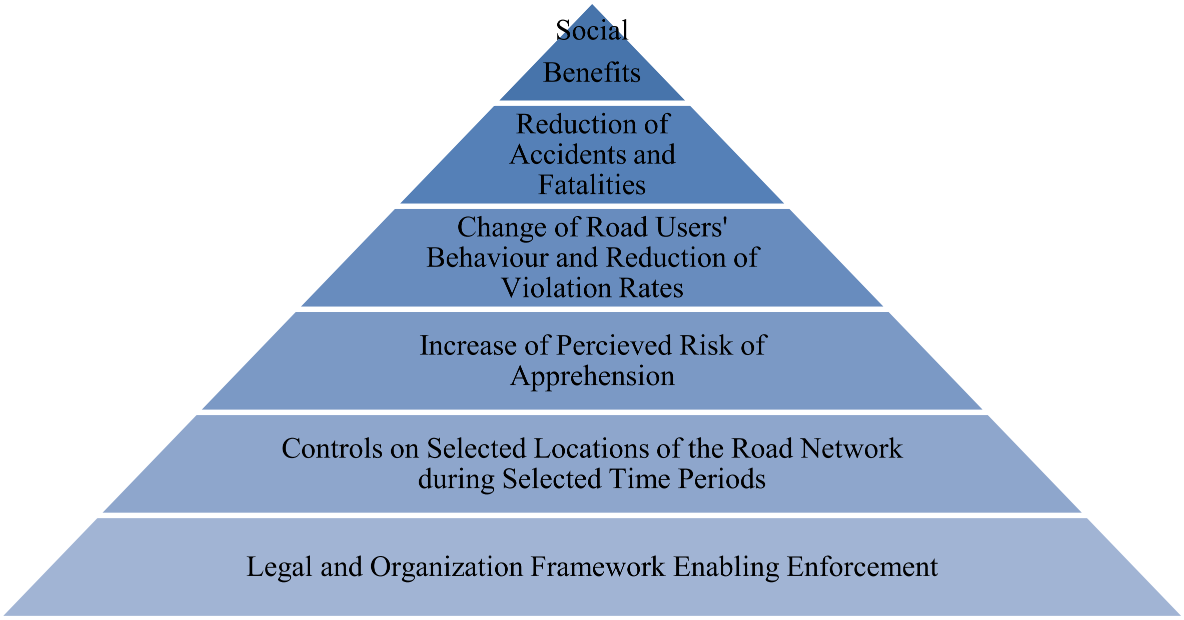


Figure 2 The Hierarchy of Road Safety Enforcement (Yannis, Louca, Vardaki, & Kanellaidis, 2004)

2.3 Photo Enforcement

2.3.1 Techniques and Equipment

Generally, two technologies are adopted in camera-based speed enforcement: photo radar and photo laser. A photo radar system usually consists of a flash camera, a Doppler radar, and a laptop for recording and transferring data, while a photo laser system usually uses LiDAR along with a flash camera and a laptop. For both methods, when a vehicle passes over the sensor, regardless of whether radar or laser is used, the camera will be triggered and two images of the violating vehicle will be captured. One is for the front of the vehicle, and the other is for the rear license plate of the vehicle (Benekohal, Hajbabaie, Medina, Wang, & Chitturi, 2008). Detailed information including violation date, time, and the speed of the vehicle will be recorded and used as evidence by the local judicial branch.

2.3.2 Types of Photo Enforcement

Photo enforcement can be performed using either fixed or mobile equipment. Normally, fixed speed camera enforcement is fully automated without involving any manpower. One of the most commonly seen applications is the intersection safety camera, which can capture not only red-light violations but also speeding vehicles. The fixed camera system is usually mounted in a box or on a pole beside the road or at overpasses or bridges. Most fixed photo enforcement is highly visible, accompanied by a warning sign installed before the camera location. However, it can also be concealed in places such as garbage bins (hidden speed camera).

Mobile photo enforcement combines the use of an advanced camera detection system with traditional manned enforcement. It can be either hand-held by a police officer or mounted on a tripod placed beside the road. Another common approach is mounting the devices on the top of or installing them in an enforcement vehicle. Mobile photo enforcement is more flexible than the fixed form due to the convenience of being able to move the equipment between locations. The mobile photo enforcement can be carried out either in an overt or a covert fashion. Overt enforcement uses community vans, which are covered by the photo of people living in Edmonton and slogans, for educating people the speeding concern. Covert enforcement uses vehicles without visible markings in order not to be distinguished from other vehicles on the road. This is such that enforcement vehicles can park at the side of a roadway without arousing the attention of travelers.

2.3.3 Limitation of Photo Enforcement

Although most of studies estimating the performance of photo enforcement show positive results, it should be noted that the effectiveness of photo enforcement is limited in terms of both time and space (Christie, Lyons, Dunstan, & Jones, 2003; Hess, 2004; Vaa, 1997). The time and space limitations are known as time halo and distance halo effects. Road users are not always clear about when and where the enforcement is going to be deployed. However, after a period of deployment, some of the frequently enforced locations may be noticed by the public. Realizing the high potential for being captured at a specific location and time, drivers can modify their driving speed when approaching those locations to avoid being apprehended; however, they may speed up again after passing a certain distance from the enforcement site. Similarly, when the public is aware of the cease of enforcement, drivers' behaviours are likely return to what they were prior to enforcement (Tay & Barros, 2009). In general, the time halo effect is the phenomenon that, after ceasing enforcement activities, the effects on an individual's driving behaviour will last only for a certain length of time. The effects of enforcement diminish with time (Tay & Barros, 2009). The results of studies about time halo vary greatly. Some found that the effects will not dissipate until three days after ceasing enforcement; others found that the effects can continue for up to two to eight weeks (Diamantopoulou & Cameron, 2002; Vaa, 1997).

As for the distance halo effect, it means the distance over which the effects of photo enforcement on drivers will continue after they pass the enforcement location. Most previous studies focus on fixed photo enforcement methods, while limited research is about mobile forms (Wang, Kim, & El-Basyouny, 2013). The distance halo effects vary in different studies due to the different enforcement characteristics, roadway features, and investigated vehicle types. An Illinois study showed that the percentage reduction of vehicles exceeding the speed limit at 1.5 kilometres downstream of the camera location was 4% to 5%, while for heavy vehicles, the result was 7% to 9% (Benekohal, Hajbabaie, Medina, Wang, & Chitturi, 2008). Another study, conducted in Singapore, found that the effective downstream distance halos on a major arterial road are 100 metres for cars and 300 metres for heavy vehicles (Chin, 1999). Although it seems that the distance halo effect is the limitation of photo enforcement, it is quite analogous to the distance spillover effect, which interprets the effect in a positive way. The spillover effect means that the influences of speed cameras are not only seen in the direct vicinity of the enforcement location but also on adjacent roadway segments (Chen, Meckle, & Wilson, 2002). Therefore, with better understanding of the effective distance influenced by photo enforcement, drivers' behaviours can be modified over a distance of several kilometres by frequently deploying intermittent enforcement. Thus, the photo enforcement effect can be improved by taking advantage of the spillover effect.

2.4 Deployment Strategies

2.4.1 Site Selection

1. Site Selection Criteria and Principles

Decisions on where to deploy enforcement are often made by government or political departments according to locally developed manuals (Alberta Solicitor General and Public Security, 2009). The criteria and principles for site selection are supposed to address the practical concerns and problems reflected by historical data. Normally, the safety condition of a specific location is evaluated in three aspects: collision history, speed violation history, and other administrative concerns. A verified collision history (i.e., within the prior 12 months) of high collision frequency and severity is considered the primary criteria for site selection (Queensland Transport; Victoria Police, 2006). A location that has experienced a high number of violations related to excessive speed or inappropriate speed is also considered to be a potential enforcement site (Queensland Transport; Victoria Police, 2006). If the speeding problem at a location is reported through complaints by the public and the perceived risk of speed-related collisions is confirmed, enforcement at that site should be considered. Moreover, site selection decisions are also subject to enforcement operation feasibility, political trade-offs, and the need of addressing special concerns; for example, enforcement is suggested at places near construction sites that face the risk of traffic trauma (Carnis, 2011).

Inappropriate locations can eliminate the effectiveness of enforcement; thus, enforcement at those locations should be avoided. Referring to the guide used in Victoria, Australia, enforcement is not recommended to be placed at the following locations: the bottoms of hills or corners unless a severe speeding problem has been validated; within 5 km of one another in the same direction; or within 200 meters of a change in speed limit (Victoria Police, 2006).

It is insufficient to select high-risk locations among numerous candidate locations by knowing only the identification criteria. A quantitative screening process involving all criteria is needed.

2. Methods for High Risk Location Identification

Various techniques and methods for identifying high-risk locations have been adopted and developed. On both the academic and practical side, most methods involve the use of a geographical information system (GIS). Normally, the entire identification process can be broken down into five steps:

- Geocode the collision data for the whole investigated area;
- Conduct a spatial pattern analysis to find out the collision distribution characteristics;
- Create a hotspots concentration map;
- Identify the unsafe locations;
- Rank and select the unsafe locations.

When analyzing the spatial patterns of collision data, two methods are usually used. One widely used method is Kernel Density Estimation (KDE), which calculates the density of collisions within a search bandwidth around those collisions. Collisions are seen as discrete events, and the goal of using KDE is to develop a continuous surface density of collisions by summing up the number of collisions within a buffer area (Truong & Somenahalli, 2011). KDE used to be applied for a 2-D space, but many studies recently extended it to a network space. No matter whether it is applied to a 2-D or network space, the statistical significance of the KDE method cannot be tested (Anderson, 2009). The other method to study the spatial pattern of collisions is investigating the spatial autocorrelation by considering the collision locations and numbers simultaneously. Geary's C Ratio and Moran's I Index are two commonly used indices to measure spatial autocorrelation. Both of the indices are global statistics, which are measures of the entire study area. To investigate the spatial variation and associations, local Moran's I and Getis-Ord Gi* statistics (a spatial statistic used for hotspot analysis) can be used (Truong & Somenahalli, 2011). Different than with the KDE method, the statistical significance for those statistics can be calculated using z-score methods (Truong & Somenahalli, 2011; Wong & Lee, 2005).

The criteria used for identifying unsafe locations will directly influence the identification results. Some studies use simple criteria such as collision counts, collision density, or collision rate. Instead of only using the absolute collision counts, collision rate per unit exposure or collision rates based on severity level can better indicate the safety problem at a specific location (Truong & Somenahalli, 2011). Usually, the typical measures of exposure are vehicle volume, pedestrian volume, and population of an area (Pulugurtha, Krishnakumar, & Nambisan, 2007). A straightforward way to identify unsafe places is to compare the value of a criterion with a preset threshold.

Other studies use a composite method that takes several factors into account concurrently. The composite method can capture the benefits of each simple method and minimize the disadvantages. In a U.S. study, they came up with two different composite methods: the sum-of-the-ranks method and the crash-score method (Pulugurtha, Krishnakumar, & Nambisan, 2007). For a specific location, the result of the sum-of-the-ranks method is its average of ranks in different simple ranking methods. The crash-score method involves normalizing the values of the results of each simple method to the same scale, so as to get a score for each method. After the normalization, the score of each simple method will be added together to get a final composite score. For both of the composite methods, either equal or different weights can be given to each simple method when summing the individual results. However, the results may be biased if using different weights. To reduce the subjectivity, weights can be determined based on the discussion result of a practitioner or expertise group (Pulugurtha, Krishnakumar, & Nambisan, 2007)

2.4.2 Program Duration and Deployment Hours

The length of time that the enforcement program lasts and the total hours when enforcement is actually in operation have direct influences on reducing speeding and collisions to an acceptable level.

The influences of the length of program on changes in collisions vary for different severity levels. A study in Queensland estimated the yearly trend of collisions at each severity level after the photo radar enforcement program was introduced (Newstead, Cameron, & Leggett, 1999). During the period from 1991 to 1994, fatal collisions reduced in the first year and the trend fluctuated during the last two years. The number of injury collisions did not see a dramatic decrease at the beginning of the program, but kept reducing steadily throughout the three years. The changing trend of property-damage (PDO) collisions was similar to that of injuries, although a slight increase occurred at the very beginning of the program (Newstead, Cameron, & Leggett, 1999).

Generally, photo radar enforcement needs less time to have an impact on reducing speed than on collisions. Usually, it takes less than one year to reduce the mean speed to be equal to or below the speed limit. As for collisions, fatal collisions are more sensitive to photo radar enforcement than either injury or PDO collisions (Wang, Barua, Li, Kim, & El-Basyouny, 2013).

Long duration of the enforcement program does not necessarily promise better results in collision reduction due to diminished effects over time, which is also deemed to be the time halo effect. To prolong the effective time, enforcement efforts should keep intensifying throughout the program (Goldenbeld & Schagen, 2005; Delaney, Diamantopoulou, & Cameron, 2003).

The required deployment hours vary according to the availability of enforcement resources and the severity of the speeding problem in different jurisdictions. In British Columbia, the photo radar program, which involved 30 covert enforcement units province-wide, reached 30,000 deployment hours during the first year, and resulted in about a 50% decrease in violations exceeding the speed limit at 16 km/h or more. However, the reduction was concentrated in the first seven months and remained at the same level during the remaining months of the year (Chen, Wilson, Meckle, & Cooper, 2000). In the Netherlands, the mobile radar enforcement program targeting 28 rural road segments was carried out for five years, and attained about 5,000 enforcement hours on average each year. During the first year, the mean speed decreased from 82 km/h to 80 km/h on roads with a speed limit of 80 km/h. The mean speed remained unchanged during the following two years, until it further declined 2 km/h during the last two years due to the doubled enforcement hours (Goldenbeld & Schagen, 2005). In Victoria, Australia, photo enforcement was conducted in both overt and covert forms, reaching about 35,000 and 11,000 deployment hours, respectively, within a year. With a mild increase in enforcement, remarkable influences on drivers' behaviours were achieved in the first six weeks after implementing enforcement (Diamantopoulou & Cameron, 2002). In Queensland, Australia, the enforcement hours, from 6 AM to midnight, were divided into two-hour sections, during which the police vehicle might remain at the same site. The number of operation hours required per week depended on the available enforcement resources (Queensland Transport; Newstead, Cameron, & Leggett, 1999).

2.4.3 Scheduling Method

1. Fixed Scheduling Method

One of the most commonly used scheduling methods is to allocate enforcement resources based on a fixed schedule. Given the exact time for visiting a specific location, the operators need to stick to the schedule to carry out enforcement. The certainty of a fixed schedule makes it more convenient to manage enforcement resources and apply specially designed strategies.

In France, a concept of Network Centric Deterrence (NCD) was put forward in the photo enforcement program. With more than 2,756 speed cameras operating throughout the public roads and highway network, the enforcement sites were distributed over the whole road network according to a predetermined schedule. The large coverage of enforcement made it difficult for drivers to avoid detection, no matter which route they took. By applying consistent rules and centralizing all the information about program operations and speed violations, the nationwide detection network achieved great results (Carnis, 2011). Although a fixed schedule provides drivers with a greater chance of successfully predicting the time and locations of enforcement, seemingly weakening the planned effects, the large coverage and unavoidability of detection resulting from the various enforcement types and the large number of deployable enforcement units effectively mitigates the disadvantage. The NCD proved to be a successful example of using the fixed scheduling method, but it is less likely to achieve similar positive effects by using this method in other jurisdictions without the support of sufficient enforcement resources.

In a study in Israel, a two-stage approach was proposed for solving the traffic police location and schedule assignment problem (Adler, Hakkert, Raviv, & Sher, 2014). In the first stage, a multi-objective linear programming model was used to identify the locations and times of activities at these locations during each shift. It aimed to maximize the police presence and conspicuousness at locations with high traffic violation frequency. In addition, the goal was to maximize the time for police to respond the call for service. In the second stage, it applied a MAXMIN interlinear program to choose the locations for a shift, in order to account for the distance halo effect. To account for the time halo effect, an integer linear program was used to minimize the repletion of locations in two contiguous shifts. This approach, tested in a case study in northern Israel, dynamically generated shift schedule on a daily basis over the planning horizon. The results showed that the sequential-shift locations, which attempted to be avoided, still existed in the schedule. However, the method has minimized this violation (Adler, Hakkert, Raviv, & Sher, 2014).

2. Randomized Scheduling

An alternative way to allocate limited devices and personnel resources is using a randomized schedule. Enforcement vehicles are deployed to randomly chosen sections of highways, where speeding issues have been identified, at random times. Without knowing the exact location and time of enforcement, drivers tend to feel that detection may occur anywhere along the road at any time, resulting in an increased subjective risk of being caught.

It was hypothesized that, compared with the fixed scheduling method, the random scheduling method could cover the same proportion of the road network with lower staff levels and achieve collision reduction with lower deployment intensity (Leggett, 1997). This approach was first tested in 1978 in the United States. The result showed that the distance halo per patrol vehicle reached 22 kilometres on average, which was about four times greater than results demonstrated in other studies (Leggett, 1997). In 1988, another study on the random scheduling method observed a 60% reduction in serious injury and fatal collisions on rural roads (Leggett, 1988). The Random Road Watch program, which is part of the photo enforcement program in Australia, also adopted the randomized scheduling method. The enforcement continued throughout the week based on computerized schedules. The time of day and the day of week of enforcement at each site was decided by enforcement operators (Leggett, 1997).

Randomized scheduling imposes less control and provides more freedom to enforcement operators to decide where to go at which time, making the deployment of enforcement more unpredictable. It is appropriate to apply the random scheduling method to situations where limited deployable resources are available.

2.5 Conclusion

The review of enforcement theory and mechanism provides a better understanding of how photo enforcement plays a role in improving road safety, which offers theoretical support for designing a framework of scheduling and deployment of MPRE.

Although many studies in the literature have documented the general or program-specified site selection criteria, it is insufficient to select high-risk locations among numerous candidate locations by knowing only the identification criteria. A multi-criteria step-by-step location screening process needs to be developed.

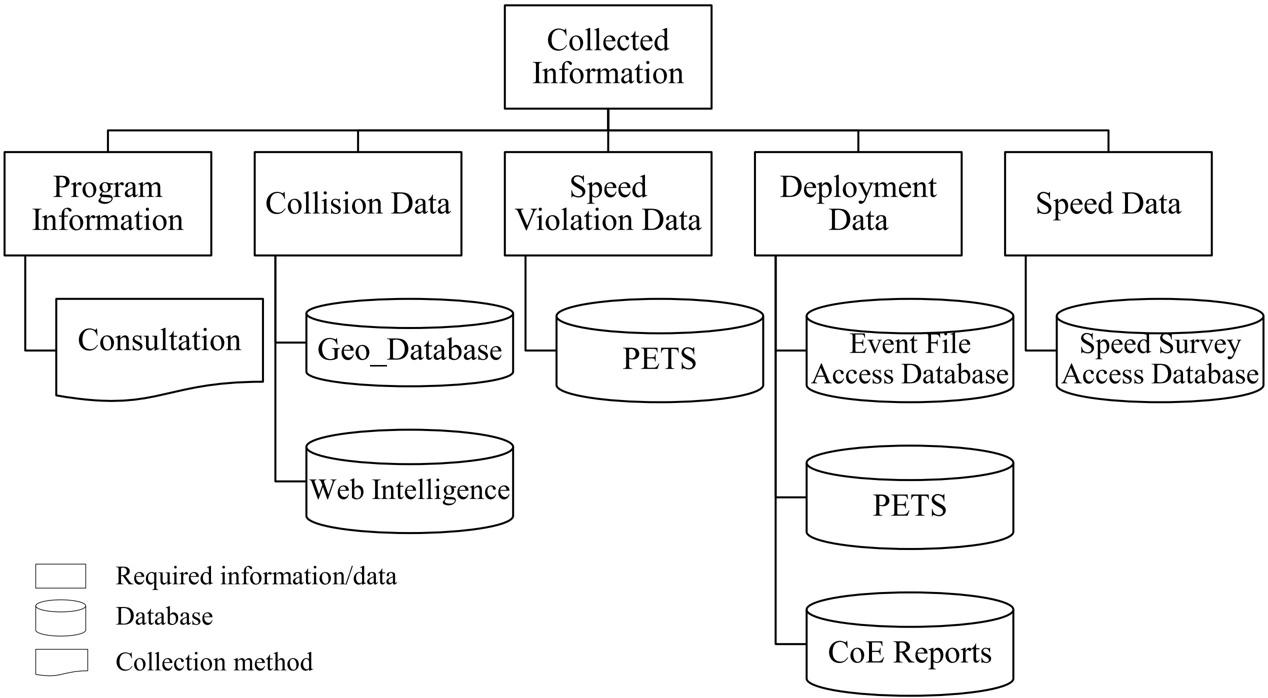
The fixed scheduling method used in France has achieved good results, but it has a high requirement for the number of available enforcement resources. In the City of Edmonton (CoE), the enforcement resources are not sufficient to support large-coverage and high-intensity enforcement needed for fixed schedules to be effective. Due to the nature of the random scheduling method, previous studies provide only a concept overview or brief introduction on the randomized scheduling method. There is no explicit description about how to design and implement the random scheduling method found in the literature. The program objectives and enforcement culture that exist in the MPRE program vary in different jurisdictions; therefore, the scheduling method and deployment strategies have to be tailored to the specific program needs and features of the local enforcement environment. Thus, a specially designed scheduling method for the MPRE program in the CoE needs to be proposed.

CHAPTER 3. LOCAL PROGRAM REVIEW AND DATA ANALYSIS

In this chapter, a review of the mobile photo radar enforcement (MPRE) program in the City of Edmonton (CoE) is presented, which gives an overview of the local program. The information provided includes the available equipment and personnel resources, enforcement locations, the current deployment strategy, and program regulations and guidelines. The local data were collected and processed to support the preliminary data analysis. The analysis results are important inputs for designing the initialization plan. Moreover, the historical data can be used in a future program evaluation. Some of the contents in this chapter have been documented in the third report "Initialization Plan for the Deployment of Mobile Photo Radar Enforcement in the City of Edmonton" (Wang, Kim, & El-Basyouny, 2014a).

3.1 Information and Data Acquisition

The most relevant data to support the design of the MPRE framework are the COE's current MPRE program operational procedures, and related historical data. Important program information includes personnel resources, equipment resources, program regulations, target locations for enforcement, and current deployment strategies. The related data can be roughly classified into collision data, speed violation data, deployment data and speeds statistics. The data/information distribution is shown in Figure 3. Figure 3 shows the information/data collected and where/how the data/information were found. The attributes of each dataset will be described in details in Section 3.3.2.



*PETS stands for Photo Enforcement Ticketing System

Figure 3 Data/Information Resources Distribution

3.2 Review of the Current Program

3.2.1 Resource Availability

In Edmonton, the Office of Traffic Safety (OTS) employs two types of technologies for mobile photo radar enforcement (MPRE): photo radar (PR) and photo laser (PL) detection systems. According to information provided by the OTS at the end of December 2013, a total of 18 units are operational and shared by all squads. Thirteen units are fitted with PR equipment: 10 are covert and three are overt. Five units are fitted with portable PL devices, the DragonCam, for covert operation. The DragonCam is a laser-based digital imaging enforcement system that uses LiDAR technology and is capable of capturing speed limit violations and violators' licence plate information. In the thesis, the improved deployment strategy is designed for only covert MPRE.

However, it is important to note that, with modifications, the proposed approach can be applied to PL deployment.

There are six enforcement squads, consisting of four PR squads and two directed enforcement (DE) squads, responsible for operating the covert and overt PR equipment, respectively. Each day, there are two shifts of covert PR and only one PR squad is deployed each shift. In the first shift, one PR squad starts at 6:00 AM and finishes at 4:00 PM (ideally operating up to nine covert PR units). In the second shift, one PR squad starts at 4:00 PM and finishes at 2:00 AM (ideally operating up to nine covert PR units). There is also one 10-hour overt PR enforcement shift deployed by DE squads each day, and one DE squad is deployed per shift. The shift start time varies from 6:00 AM to 12:00 PM, and enforcement operates only during daylight hours. There is only one shift for overt MPRE each day. This shift usually partially overlaps the AM and PM covert PR shifts.

A single enforcement unit consists of an equipment operator, a vehicle, and enforcement equipment. The squad details, including the ideal number of personnel in each squad, the organizational structure of each squad, the ideal and actual number of sites enforced by each unit during one shift, and the devices used by each squad, are summarized in Table 2.

Table 2 Squad Details

<table>
<tr><th colspan="2"></th><th colspan="2">DE Squad</th><th colspan="2">PR Squad</th></tr>
<tr><td colspan="2">Ideal staff level</td><td colspan="2">1 sergeant and 4 operators operating 5 PL and 1 overt PR community van (CV)</td><td colspan="2">1 sergeant + 8 operators = 9 TOTAL</td></tr>
<tr><td colspan="2" rowspan="4">Current staff level</td><td rowspan="2">DE 1</td><td rowspan="2">1 sergeant and 3 operators operating 5 PL and 1 overt PR CV</td><td>SQ 1</td><td>1 sergeant + 7 operators = 8 TOTAL</td></tr>
<tr><td>SQ 2</td><td>1 sergeant + 7 operators = 8 TOTAL</td></tr>
<tr><td rowspan="2">DE 2</td><td rowspan="2">1 sergeant and 3 operators operating 4 PL
and 1 overt PR CV</td><td>SQ 3</td><td>1 sergeant + 7 operators = 8 TOTAL</td></tr>
<tr><td>SQ 4</td><td>1 sergeant + 4 operators = 5 TOTAL</td></tr>
<tr><td rowspan="2"># of site/ shift/unit</td><td>Standard</td><td colspan="2">2</td><td colspan="2">2</td></tr>
<tr><td>Actual ability</td><td colspan="2">3-4</td><td colspan="2">3</td></tr>
<tr><td colspan="2" rowspan="3">Device</td><td colspan="2">5 covert PL</td><td colspan="2">10 covert PR</td></tr>
<tr><td colspan="2">1 overt PR CV</td><td colspan="2" rowspan="2">1 CV* when lacking covert trucks</td></tr>
<tr><td colspan="2">1 CV* used by PL operator when lacking PL truck</td></tr>
</table>

*CVs are used by regular PR squads and by PL enforcement if regular vehicles are not available.

3.2.2 Enforcement Sites

In Edmonton, there are currently 1,157 enforcement sites, including 1,103 PR sites and 54 DragonCam sites. Within the research analysis period, April 2009 and March 2013, 887 PR sites were enforced at least once; these PR sites are the major part in the candidate site pool for the pilot study of MPRE program redesign. Details about the composition of the candidate site pool will be described in Section 4.2.1.

3.2.3 Current Deployment Strategy

3.2.3.1 Site Selection

Sites are identified based on public complaints, special requests, and the provincial automated enforcement guidelines. The senior speed management coordinator is provided with a site list, which includes about 700 sites. Currently, 50 to 70 sites, which are selected from the 700 sites, are included in a weekly schedule, which is created for operators based on information about speed violation rates, site priority, citizen complaints, high-risk time-of-day and day-of-week, and weather conditions. Sometimes squads are deployed according to a pre-set plan that is developed to respond to special requests for enforcement.

3.2.3.2 Vehicle and Personnel Scheduling

Schedulers typically assign operators a truck or a van to use each shift. For photo radar, the equipment is in the truck and does not move between vehicles. For PL systems, which are portable and fit in a suitcase, the operator usually uses the same unit and the same vehicle each shift.

Typically, operators arrive at the OTS, have a brief meeting with their squad members, do their start-up tests, and then travel to their first enforcement site. They set up at a site and spend a few hours there. Typically, the deployment duration at a location ranges from one hour to four hours. However, the minimum duration could be reduced according to field conditions. If few speed violations are observed, the operator may proceed to another enforcement site. During a shift, operators may move between sites, but they need to return to OTS at the end of the shift. Operators normally take a 30-minute break between their first and second site deployment on a given shift. For the AM shift, which is supposed to run from 6:00 AM to 4:00 PM, the actual enforcement usually runs from 7:00 AM to 3:00 PM or later, while the rest of the time is used for travel.

Squads work four days on and then have four days off. Operators who work for 10 hours must rest at least eight hours before their next shift. Enforcement is deployed on all non-holiday days around the year. There is no enforcement deployed on the whole day of December 25 and

January 1, and no shift on the third watch, which covers the late afternoon and evening, on December 24 and December 31. All other holidays have regular shifts.

3.2.3.3 Deployment Instructions

1. Time of Deployment

There is no specific requirement for the time of day and day of week to deploy enforcement at a particular site. This is mainly decided by the operators. However, some sites are assigned or avoided during specific times of the day based on speed survey information. For example, it is standard to avoid deploying enforcement on some road segments during rush hours, as the roadways are too congested and all vehicles travel well below the speed limit; however, some sites experience high volumes of commuter speeders during rush hours or after major events, so these sites are targeted specially during when a higher speed violation rate is observed.

2. Frequency

Sites are usually visited by different operators more than once in a scheduling cycle. Normally, there is no specific requirement on the deployment frequency for a given site; however, some sites, especially the newly added ones, may require a minimum number of visits.

3. Requirement for Enforced Sites in Each Quadrant

In the CoE, there are five police divisions: North, West, Downtown, Southeast, and Southwest. As per the scheduling decision made by OTS, the smaller Downtown area is combined with the larger North area to efficiently distribute enforcement resources; therefore, there are four enforcement quadrants. There is neither a requirement on how many sites from each quadrant should be included in the schedule nor a requirement on how many sites from each quadrant must be visited in an enforcement cycle. The sergeants assign operators to different police divisions when scheduling. Each squad assigns one or two units to each of the four quadrants each shift.

3.2.3.4 Schedule Adjustment

1. Activate or Add a Site

The schedule is adjusted every week and varies from week to week; some sites are visited more frequently than others. When approving a new enforcement site to include in the monthly schedule, if the site was previously active and exists in the database, it only needs reactivation. If the site has never before been enforced and there is no data supporting the existence of a speeding problem at the location, a speed survey may be ordered. Because the speed detection device is imbedded in the roadway, the speed survey cannot be performed during winter once there is snow on the ground. If the speed survey results indicate a speeding problem, the site's collision records in the past three years will be reviewed. Then, the area will be validated for enforcement feasibility and operator safety. After meeting the aforementioned requirements, a request is sent to the Edmonton Police Service to obtain approval for the new enforcement site (Alberta Solicitor General and Public Security, 2009). Excluding the time spent waiting for the speed survey results, the approval process, which starts from site assessment and ends with inputting the site into the system, usually takes five to 11 business days. If speed surveys are required, the process can take approximately five months, as the results are needed for justifying the creation of new sites (Wang, Kim, & El-Basyouny, 2014a).

2. Deactivate or Remove a Site

Changes occurring at approved speed camera sites may affect the sites' suitability for operations. These sites should be investigated to determine whether they need to be deactivated from the PR access database either permanently or temporarily, depending on the nature of the underlying issues. At a minimum, mobile photo enforcement sites will be assessed annually by the supervisor of the mobile enforcement program. The enforcement effectiveness at sites will be assessed based on not only a comparison of speed survey data from year to year (if available) but also community complaint information provided to OTS and the site's speed violation counts. Sites deemed to be non-effective will be deleted from the site list. The PR access database and PR site spreadsheet, as well as Geo-Maps, will be updated.

3.3 Data Collection, Processing, and Analysis

Data are the basis used to objectively understand the operation of the current MPRE program and find out the deficiencies that should be improved in program redesign. Since the data are stored in different databases, they need to be collected from different data resources and gathered together. As the data format varies for each database, necessary data processing is required to convert all the data to the same format. The historical data analysis results provide support and guidance for redesigning the MPRE program. Once the program design is operationalized, the historical data can be used in before-and-after analysis when evaluating program performance.

3.3.1 Data Requirement

According to the main tasks involved during different time periods throughout the MPRE program, the entire process can be generally divided into three continuous stages: pre-deployment stage, deployment stage, and post-deployment stage. In each stage, a variety of data are required, and these data are inter-related. The data required in each stage are summarized by reviewing related information in previous MPRE programs that have been conducted in other jurisdictions.

1. Pre-Deployment Stage Data

In the pre-deployment stage, high-risk locations are selected and the deployment strategy is determined.

When screening speeding-prone locations, the historical data, including collision, speed-related violation and speed, need to be analyzed. For collision data, it is necessary to know the number of each type of collision, the number of collisions at each severity level, and the collision density in a particular area. Changes in collision, such as reduction and fluctuation, will be recognized by analyzing the historical collision data. For speed violations, it is necessary to know the number or the percentage of violations exceeding the speed limit at different speed levels. As for the speed data, the requisite data includes the mean speed or 85th percentile speed, speed limit, and trigger speed at enforced and non-enforced segments. A list of potentially enforced locations is the output of this procedure.

Besides the data used for screening enforcement locations, traffic data and other information are also needed for developing schedules and deployment strategies. The traffic data contain traffic volume and degree of pedestrian presence; other information includes roadway design features, installation of traffic control devices, weather conditions, and technical operation feasibility.

2. Deployment Stage Data

Enforcement resources are dispatched at the deployment stage according to the pre-determined deployment strategy and schedules.

Data related to this stage are either about scheduling or actual enforcement results. Information about scheduling includes deployment duration, frequency, start and end time of each visit, while data related to the output of deployment contain violation numbers, collision numbers, traffic volume, the number of issued tickets, and other information about each enforced location, such as pavement conditions, traffic control devices, and road design.

3. Post-Deployment Stage Data

After a certain time of enforcement, evaluations on enforcement performance are to be conducted in the post-deployment stage.

The evaluation usually requires data including (i) speed data at enforced and non-enforced locations (i.e., reduction in mean speed and speeding vehicles, etc.); (ii) the number of traffic collisions (i.e., reduction in collision counts and reduction of collisions at each severity level, etc.); (iii) the number of issued tickets; and (iv) road layout and traffic features of the sites (i.e., segment length, width, number of lanes, speed limit, AADT, site type, etc.).

3.3.2 Data Collection

Besides the required data summarized in Section 3.3.1, what data is collected also depends on the data availability.

In the CoE, MPRE targets, but is not restricted to, locations with high speed violations, high collision counts, high pedestrian volumes, and special administrative requirements (Alberta Solicitor General and Public Security, 2009), which is in line with the concept of problem-oriented enforcement (Goldstein, 1990).

PR sites are locations that are enforced using photo radar. A PR site is a road segment with a singular directional attribute. In the CoE, 887 PR sites, which were enforced at least once from April 2009 to March 2013, make up a major part of the enforcement site pool. The historical data for each PR site include records for collisions, deployment, and enforcement. Detailed information is shown in Table 3.

Table 3 Historical Data for PR Sites before Segmentation

Dataset	Data Resource	Description
Collision Records	• Geo-Database (2006.01 – 2013.09) • Web Intelligence (1992.1 – 2013.10)	• Location and Date • Severity • Cause • Direction
Deployment Data	• Photo Enforcement Ticketing System (PETS) Database (2005.01 – 2013.10)	• Location and Date • Length of enforcement • Frequency • Traffic Count
Enforcement Statistics	• PETS (2005.01 – 2013.10) • Event File Access Database (2011.05 – 2013.09) • CoE reports (2009.01 – 2013.03)	• Location and Date • Speed • Violations • Issued tickets

To expand the potential enforcement site pool, the proposed method also considers speed survey (SS) sites. SS sites are locations where speed surveys have been conducted because of public complaints about speeding, but they may or may not have been approved for enforcement for various reasons, such as inconvenient parking for enforcement vehicles, at the time of assessment. However, it is highly possible that these sites exhibit serious speeding problems. These at-risk locations should keep being monitored and reassessed for enforcement feasibility. There are 828 SS sites marked as points without singular directional attributes in the Geo-Database managed by OTS. Each SS site has historical collision and speed data, as illustrated in detail in Table 4.

Table 4 Historical Data for SS Sites before Segmentation

Dataset	Data Resource	Description
Collision Records	• Geo-Database • (2006.01 – 2013.09) • Web Intelligence (1992.01 – 2013.10)	• Location and Date • Severity • Cause • Direction
Speed Statistics	• Geo-Database (2006.01 -2013.09) • Raw Data Files (2009-2013) • Speed Survey Access Database (2009.04 – 2013.10)	• Location and Date • Direction • Speed Measures (i.e. average, variance, etc.) • Compliance/Violations

As shown in Table 3 and Table 4, the historical data that cover different time periods are stored in several databases. The common period covered by all databases is from April 2009 to March 2013; therefore, this was taken as the research analysis period.

3.3.3 Data Processing

3.3.3.1 Segmentation

A typical PR site was a section of road that may either span between two intersections or across one intersection. A SS site was a point at which the speed detector is imbedded under the pavement. So that traffic safety analysis techniques can be applied, the consistent segmentation process was applied for all PR and SS sites.

1. Segment Definitions and Assumptions

There are general definitions of each type of segment:

- Arterial segment: arterial between two signalized intersections
- Collector road segment: collector road between two intersections and crossed by either an arterial or a collector road

- Local road segment: local road between two intersections and crossed by either an arterial or a collector road
- Freeway segment: freeway between two interchanges

The possible combinations of intersection types are listed in Table 5.

Table 5 Possible Combinations of Intersections

Road type	Arterial segments	Collector road segments	Local road segments	Freeways
Possible situations	AA-AA AA-AC AC-AC AC-AL (dead-end) AL-AA (dead-end) AL-AL (dead-end)	CC-CC CC-CL (dead-end) CL-CL (dead-end) AC-CL (dead-end) AC-AC AC-CC	LL-LL (dead-end) CL-LL (dead-end) CL-CL AL-LL (dead-end) AL-CL AL-AL	two interchanges

The segmentation was conducted based on three general assumptions:

(1) A single segment may sometimes contain multiple PR and (or) SS sites. Two overlapped PR sites are merged as one segment.

(2) Directional information is assigned to each SS segment according to the direction for which speed data is available.

(3) A freeway is a controlled-access highway designed for high-speed vehicular traffic, with no interruption of traffic signals, intersections, and property access. The entrance and exit to the highways are usually provided at interchanges. Based on the definition of freeway, nine roads were identified as freeways in the CoE by checking Google Maps to verify whether there are successive interchanges along the road:

- Whitemud Drive
- Anthony Henday
- Yellowhead Trail
- Calgary Trail (partial)
- Gateway Boulevard (partial)

- 97 Street (from 176 Ave. to Yellowhead Trail)
- St. Albert Trail (starting from Yellowhead Trail)
- 170 Street (from Yellowhead Trail to Whitemud Drive)
- 75 Street (partial)

2. Special Segmentation Cases

In reality, the road network is complex; therefore, some segmentation must be done outside of the general definitions. There are three scenarios that require special consideration:

(1) An arterial segment ends when it meets a dead-end, river bend, or the city boundaries regardless of whether or not there is a signalized intersection.

(2) A collector and (or) local segment ends when it meets a dead-end, river bend, or the city boundaries.

(3) All segment types end before a roundabout.

3. Segmentation Method and Result

Due to the diversity of scenarios, in order to ensure the segment identification accuracy, Segments were identified manually with the aid of commercial GIS software (GeoMedia Professional). The identification process was divided into three steps:

(1) Overlap the traffic signal layers with the road network layer; and

(2) Highlight roads in the light of their functional classification (arterial, collector, or local, with different colours for each); and

(3) Identify each segment based on the aforementioned definitions.

Originally, 1,294 SS segments were identified. However, some SS segments overlap with PR segments. SS segment sets need to be merged with PR segment sets to ensure that the same information is not recorded twice. Recalling the segmentation process for both original PR sites (which were marked as road segments) and SS sites (which were marked as points), new SS sites were identified by transforming the points into longer sections that include the detector-location point. New SS sites comply with the definition of the corresponding segment type (arterial, collector, or local). To meet the new segment type definition, some original PR sites were combined to make new PR sites, while some original sites translated directly into new PR sites. Therefore, an SS site is either wholly covered by a PR site or wholly removed from a PR site (non-overlapping). Only when the SS site is non-overlapping with the PR site, is it defined as a new SS site. Otherwise, when an SS site is covered by a PR site, only the PR site record is kept and the corresponding SS site information is deleted.

After removing the repeated segments, the PR and SS locations were classified by road type into five groups. The results are shown in Table 6.

Table 6 Segmentation Results

Segment Type	**PR segment**	**SS segment**
Arterial	236	266
Collectors	362	350
Local	110	221
Freeway	34	19
Ramp	9	0
TOTAL	751	856

These newly defined segments will be used for enforcement deployment, scheduling, and evaluation. Therefore, from this point onward, “site” in this thesis refers to a newly identified segment, rather than an original site.

3.3.3.2 Unifying Data Format

Because the data shown in Table 3 and 4 were stored in different databases, the data formats were not consistent. For the data from the same database, the formats may vary by years. For instance, some of the SS location names were in abbreviated version, while others were in the expanded version. For the same type of data from different databases, some of the data were stored in text-based form, others were in coding form. Therefore, changes in the data formats were made to keep them in a consistent manner.

3.3.3.3 Merging Data Sets

After segmentation, a newly identified site may cover more than one original site. The new site’s data can be obtained by aggregating the data of the original sites that it covers.

For PR sites, deployment, enforcement, and collision data were aggregated and linked to each site. The deployment and enforcement data include deployment length, frequency, traffic count, speed violations, tickets, and speed, while collision data include collision severity and cause, travel direction of the primary object, and date of the collision. For SS sites, speed statistics and collision records were linked to each site. Speed statistics contain information about date, speed compliance, and speed under different measures (i.e., average, variance, 85th percentile, etc.), while collision data include collision severity and cause, travel direction of the primary object, and date of the collision.

Deployment and enforcement data for PR sites and speed statistics for SS sites were linked to the newly identified sites using a site ID determined prior to segmentation. After being matched, the data were aggregated on a monthly basis using MATLAB 7.0.

As for collision records, since there was no attribute that directly links collisions to each segment, manual aggregation was required, which included three steps:

1. Determine the segment's collision points by referring to the relative position of collision points and segments demonstrated on maps in the commercial GIS software (GeoMedia Professional or ArcGIS 10.1);
2. Filter out collisions that did not occur at the midblock point; and
3. Aggregate collision numbers in terms of severity and cause for each segment on a monthly basis using MATLAB 7.0.

At this stage, only midblock collisions have been considered. Since the purpose of using collision statistics is to identify target locations for MPRE, rather than identify locations based on general deterrence or specific deterrence, locations should be identified as those that incur a high number of collisions that can be effectively reduced by MPRE. MPRE mainly affects midblock collisions. In contrast, although the effects of MPRE can spill over to adjacent intersections, intersection-related collisions are influenced by many other factors, including traffic control devices, intersection design, and pedestrian volume. If intersection-related collisions were considered, it is quite possible that a location with a high number of intersection collisions but few midblock collisions would be recognized as high risk; however, PR enforcement has a limited effect on such locations.

3.3.4 Preliminary Data Analysis Results

The preliminary data analyses were performed by another team member. The results of his work support this research and are presented in this section.

The descriptive data analyses were performed to understand the operation of the current MPRE program in the CoE. Based on the historical data, a generalized linear model was used to examine the relationship between city-wide collisions and deployment intensity levels. According to the goodness-of-fit of the model and the significance of the enforcement variable, proxies of enforcement indicators were recommended. Further investigation to determine the minimum effort required to achieve expected results and the suitable deployment intensity could provide guidance in designing optimal deployment strategies. Moreover, a before-and-after analysis was performed to examine the effects of MPRE on collision reduction at the enforced site level. Based on the analyses, the following conclusions were drawn and will be incorporated in the deployment strategy and scheduling method (Li, 2014):

1. The violation rate seems to be irrelevant to collision occurrence at a specific location.

2. For sites on arterial, collector, and local roads, the distributions among the four categories (high violation, high collision; high violation, low collision; low violation, high collision; and low violation, low collision) are different.

3. Three collision peaks were identified by analyzing the distribution of city-wide mid-block collisions from April 2009 to March 2013: AM peak (8:00–9:00 AM), PM peak (4:00–6:00 PM), and midnight peak (approximately 1:00 AM).

4. The PM peak for collisions was more significant than the AM peak. Both their distributions were in accordance with traffic volumes. The midnight peak was not accompanied by an increase in traffic volume.

5. Two speed violation peaks were identified: Noon peak (11:00 AM–12:00 PM) and midnight peak (11:00 PM–1:00 AM).

6. Speed violation peak hours are not consistent with collision peaks. The midnight peak exhibited a more severe speeding problem.

7. Deployment efforts drop greatly between 2:00 PM and 4:00 PM when shift changeover occurs. Particularly on arterials and collector roads, the enforcement efforts are not sufficient to meet the demand of PM collision peaks.

8. For both total collisions and speeding collisions, enforcement variables including deployment hours, deployment frequency, the number of issued tickets, checked vehicles, average deployment hours, and the number of enforced sites were all negatively significant. However, a similar result was not observed for severe collisions.

9. Considering the degree of variable significance, the number of deployment hours and the number of enforced sites are recommended as the proxies for enforcement indicators.

10. The minimum enforcement efforts required to achieve collision reduction are 1,348 deployment hours per month and 112 enforced sites, while enhanced results can be obtained from 3,079 deployment hours per month and 251 enforced sites.

11. It is suggested that deployment be carried out at high intensity (greater than 15 hours per site per month) or low intensity (0 to 5 hours per site per month).

12. To achieve same level of collision reduction, higher deployment intensity is required for sites on arterials than for sites on collector or local roads.

13. Continuous enforcement is more effective in reducing collisions.

3.4 Conclusion

The MPRE program in the CoE currently employs two types of enforcement technologies: photo radar (PR) and DragonCam. DragonCam is deployed in an overt form, while PR is used for both overt and covert enforcement. In this research, we focus only on the improvement of deployment strategy for covert PR enforcement. The previous enforcement locations (PR sites) were re-identified by a segmentation process. To expand the candidate site pool, locations where speed surveys have been completed were added as potential enforcement sites. Instead of providing enforcement operators a deployment schedule, the current deployment strategy allows enforcement operators the autonomy to decide what time of day and how long to stay at a specific site based on their judgment and experience.

By performing preliminary data analyses, violation and collision peak hours were identified, and the proxies of the performance indicators were determined. The minimum deployment level that can achieve the desired reduction in collisions was then able to be found. These findings will help operators make deployment-related decisions.

The program review and data analysis results provide important information for program design, which is described in detail in Chapter 4.

CHAPTER 4. PROGRAM DESIGN

This chapter presents the whole process of program design. First, a multi-criteria site identification and priority-based sit selection process is proposed. Each site is assigned an enforcement priority index, which accounts for collision number by severity level, violation numbers, and roadway types. Second, the enforcement site list is updated on a monthly basis, and the schedule is generated weekly. The number of sites in the monthly site list and the deployment frequency at each site depend on the availability of enforcement resources and capability. Third, a randomized scheduling method and a deterministic scheduling method were proposed. Finally, some guidelines for long-and short-term evaluation and program adjustment are outlined.

Some of the contents in this chapter have been documented in the third report of the optimization of mobile photo radar enforcement program (Wang, Kim, & El-Basyouny, 2014a) and a paper that is under review for publication (Wang, Kim, & El-Basyouny, 2014b).

4.1 Overview

4.1.1 Mechanism of the Program Design Process

The basic idea behind the establishment of the MPRE program design process comes from the mechanism of the closed-loop control system from classical control theory. A closed-loop control system consists of forward loops and feedback loops. The proceeding outputs will be incorporated into the adjustment of inputs for the next cycle through the feedback loop and consequently regulate the new outputs through the modified inputs and forward loop of the system (Wang, Kim, & El-Basyouny, 2014a).

The selected sites and available enforcement resources are the inputs to the process, while the evaluation results of enforcement performance are the outputs of the process. A certain amount of enforcement potentially leads to a certain level of reduction in violations or collisions, which is the so-called dose-response effect that is a result of the forward loops (Newstead, Cameron, & Leggett, 1999). Procedures for site selection and the design of deployment strategies will be adjusted according to the evaluation results so that the modified inputs will result in improved enforcement performance (Wang, Kim, & El-Basyouny, 2014a).

4.1.2 Flowchart

The program design process includes five main parts, as shown in Figure 4. The work of Part 1 has been discussed in Chapter 3. Site identification (Part 2) and enforcement resource scheduling (Part 3) will be described in detail in the following subsections. Program evaluation is the last part of the process. The program evaluation guidelines regarding the timeframe of evaluation and possible performance measures will be provided. The more detailed step-by-step instructions will to be supplemented in a later stage of the program.

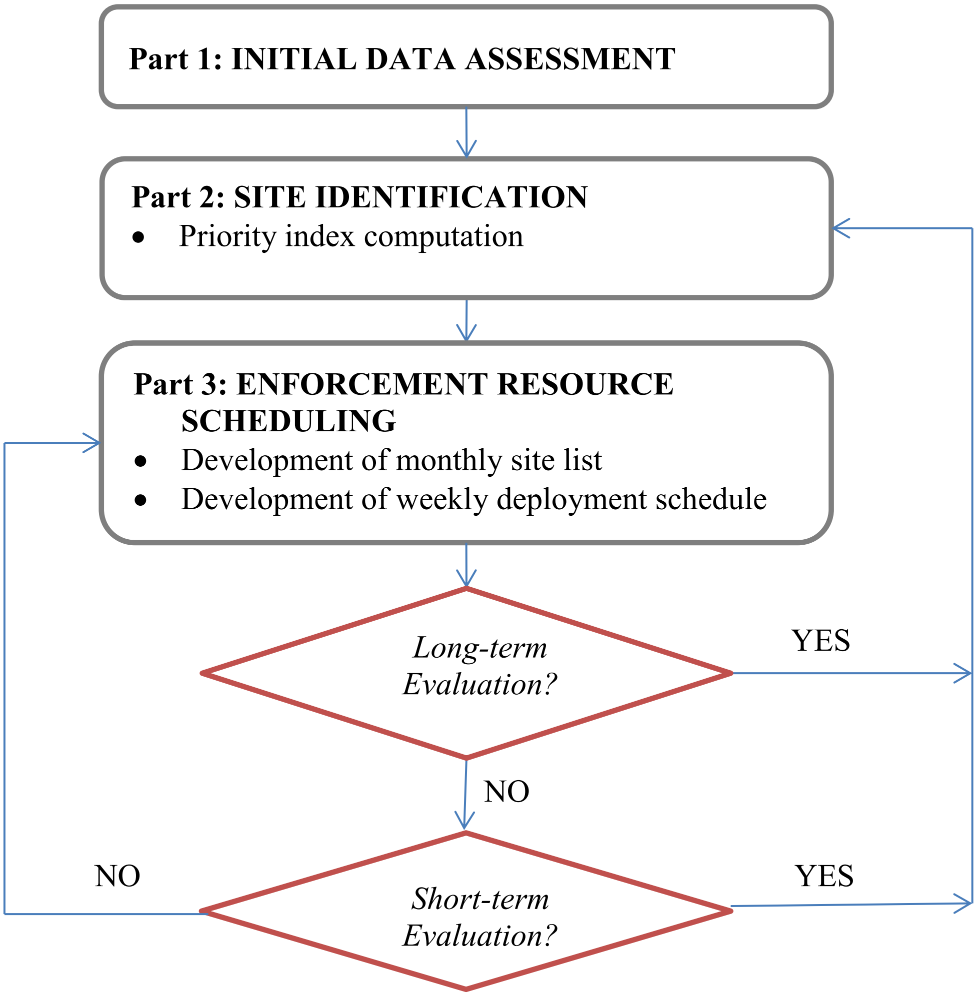


Figure 4 Flowchart of the Program Design Process

4.2 Site Identification

4.2.1 Composition of the Enforcement Site Pool

The enforcement site pool (referred to as "site pool" for short throughout the rest of the paper) consists of three sub-pools: PR sites, SS sites, and special consideration (SC) sites.

For the PR site sub-pool, PR sites are enforced by photo radar and are located on arterial, collector, or local roads. Each PR site has records of historical deployment and collision data. For the SS site sub-pool, SS sites underwent a speed survey and are located on arterial, collector, or local roads. Speed statistics and collision records are available for each SS site.

In the SC site sub-pool, some of the SC sites are PR sites and SS sites that are located on either freeways or ramps; these are classified as SC for three specific reasons:

1. Freeways are managed by different administrations; some are controlled by the City of Edmonton (CoE), while others are provincial property.

2. Traffic flows on freeways are not interrupted by traffic control devices, so vehicles are usually travelling at relatively high speeds.

3. The geometric features of freeways and ramps are different from the geometric features of other types of roads.

Other SC sites include, but are not limited to, construction sites, locations where there are special events (e.g., festivals, sports games, etc.), and neighbourhood locations (e.g., vicinity of schools, playgrounds, etc.); these locations have received public complaints about traffic safety issues and urgently require enforcement.

4.2.2 Identification of Unsafe Sites

Speed violations and speed-related collisions are the main problems threatening road safety. The road type of a site location influences the number of speed violations and collisions. Therefore, road type, the number of speed-related violations, and the number of collisions are considered when assessing the safety condition of a site.

In this research, only speed-related collisions that occurred at midblock are considered. Although the effects of MPRE can spill over into adjacent intersections due to the distance halo effect, how MPRE impacts intersection safety has not been explored in previous studies. Additionally, recognizing that factors such as traffic control devices, intersection design, and pedestrian volumes can influence the number and type of intersection collisions, sites with a high number of collisions, of which a small percentage are midblock collisions, could potentially be identified as target location if all types of collisions are considered. However, MPRE may have limited impact on such locations.

The reason for considering road type is that the type of road on which a site is located affects the number of speed violations and collisions (Li, 2014; Wang, Kim, & El-Basyouny, 2014a). The analysis of historical data from the CoE demonstrated that the majority of speed violations and collisions occurred on arterials, followed by collector roads (Li, 2014). Only a small number of speed violations and collisions occurred at local sites (Li, 2014). The average length of active PR sites in CoE is 963.1 metres, 709.1 metres, and 573.5 metres for arterial, collector, and local sites, respectively (Li, 2014). Arterials usually have multiple wide travel lanes in each direction, while collector and local roads typically have two travel lanes with parking on both sides. The longer the segment and the wider the segment, the more speed violations and collisions are likely to occur (Li, 2014).

To assess the risk of collision and speed violation, a Priority Index (*PI*) is computed for each site. The priority index computation process is divided into three steps. From this point onward in the thesis, “collision” refers to “midblock collision”.

Step 1: Normalization of Midblock Collision and Speed Violation Data

The number of collisions and speed violations for a site usually vary greatly. From April 2009 to March 2013, among all PR sites, except for those located on freeways and ramps, the total speed violation counts per site ranged from zero to 12,359 with a mean of 265, while the total collision number per site ranged from zero to 104 with a mean of 5. Moreover, speed violation can be detected only when a speed survey or MPRE is taking place; however, collision data can be collected continuously.

The collision and speed violation data are normalized separately before combining them with the assigned weights. First, the number of speed violations is divided by the hours of observation due to the fact that the total time taken for collecting violation data varies greatly among different sites. Second, normalization for speed violation and collision should be performed for PR, SS, and SC sites separately by road type to eliminate potential bias due to categorical differences in segment length and lane widths. However, SC sites, particularly those requiring temporary enforcement due to special events, may lack historical speed violation records. In this case, only the normalization of collision data is needed. The normalized values are computed using the following formula (Shyamal & Squire, 2006):

$$V_i^* = \frac{V_i/T_i - V_{nt}^{min}}{V_{nt}^{max} - V_{nt}^{min}} \tag{4.1}$$

$$\mathrm{C}_{ij}^* = \frac{\mathrm{C}_{ij} - C_{ntj}^{min}}{C_{ntj}^{max} - C_{ntj}^{min}} \tag{4.2}$$

Where,

V_i^* = normalized speed violation counts of site i, $[0,1]$,

C_{ij}^* = normalized value of midblock collision of site i at severity level j, $[0,1]$,

V_i = the total number of speed violations at site i,

C_{ij} = the total number of midblock collisions at site i with severity level j,

T_i = total observed hours for speed violations at site i,

V_{nt}^{min} and V_{nt}^{max} = the minimum and maximum values of speed violation per hour among road type t in site group n,

C_{ntj}^{min} and C_{ntj}^{max} = the minimum and maximum values of midblock collision at severity level j among road type t in site group n ,

i = site's number, site i has road type t,

j =F, I or P, collision severity level (F is fatal, I is injury, and P is property-damage-only),

t = A, C or L, road type (A is arterial, C is collector road, and L is local road),

n = site group identifier; 1 represents PR sites, 2 refers to SS sites, and 3 indicates SC sites.

The normalization, which takes road type into consideration, ensures both speed violations and collisions can be considered in the combined score (UI as shown in Step 2) in a balanced way.

Step 2: Compute an Urgency Index (UI) for Each Site

Each site is given an Urgency Index (UI), which combines the impacts of speed violations and collision frequency and severity. The urgency index (UI) is computed by the following equation:

$$UI = \alpha_j C_{ij}^* + \beta V_i^* \tag{4.3}$$

Where,
UI = the urgency index,

C_{ij}^* = normalized value of midblock collision of site i at severity level j, $[0,1]$,

V_i^* = normalized speed violation counts of site i, $[0,1]$,

α_j and β = (constant) weights for midblock collision of severity j and speed violation counts.

The coefficients α_j and β typically represent the costs of collisions and violations respectively (Truong & Somenahalli, 2011; Pulugurtha, Krishnakumar, & Nambisan, 2007; De Leur & Milner, 2011). The values of the collision weighting factors, α_j, can be determined based on the cost of collisions.

The value of α_j equals to the ratio of direct collision costs of severity j to PDO:

$$\alpha_j = \frac{DC_j}{DC_P} \tag{4.4}$$

Where,

α_j = collision coefficient,

DC_j= direct cost of collision with severity level j.

The cost of speed violations can be estimated as the proportionally combined cost of injury and fatal risks resulting from excessive speed over the speed limit (Ayuso, Guillén, & Alcaniz, 2010). Excessive speed increases the potential collision risk at different severity levels (Nilsson, 2004). The cost of a speed violation can be computed using the equation below:

$$EC_V = p_I DC_I + p_F DC_F \tag{4.5}$$

Where,

EC_V = the estimated cost of a violation due to excessive speed,

DC_I and DC_F = the direct cost of injury and fatal collision, respectively,

p_I and p_F = the estimated probability of an injury collision and fatal collision, respectively.

Probabilities p_I and p_F can be estimated from local data. To keep the same baseline, the speed violation coefficient β is the ratio of the estimated cost of a speed violation to a PDO collision.

$$\beta = \frac{EC_V}{DC_P} \tag{4.6}$$

Where,

β = speed violation coefficient,

DC_P = direct cost of PDO collision.

The proposed method can be improved by calculating injury and fatal risk values for each speed limit category, but only if the related data are available and accurate. Before being normalized, violations need to be categorized into groups according to how much the recorded speed exceeded the speed limit. The estimated cost is computed using the following equation:

$$EC_{Vs} = \sum_{s} (p_{Is} DC_I + p_{Fs} DC_F) \tag{4.7}$$

Where,

s = speed limit violation, 0 to 10, 10 to 15, ... , 25 to 30, km/h,

EC_{Vs} = the estimated cost of a violation occurring at s,

p_{Is} and p_{Fs} = the estimated probability of injury and fatal risk, respectively, at s.

For new SC sites, the historical speed violation data are not always available. Therefore, only collisions need to be considered in the computation of UI for a SC site.

Step 3: Compute A Priority Index (PI) for Each Site

A site's UI value represents the degree to which enforcement is needed at the site (basically, its priority among all sites) due to speeding and safety concerns. Because the primary purpose of MPRE at a PR or SS site is to address the site's speeding issues, for PR and SS sites, $PI = UI$. For a SC site, in addition to the severity of the speeding problem represented by the value of UI, the PI for each SC site also reflects the enforcement required for the purpose of addressing special concerns, represented by the special requirement index (SI). SI is based on the theory of the analytic hierarchy process (AHP), which quantifies the importance of the problem's elements as numerical values compared over the entire range of the problem (Saaty, 1990). A scale consists of four qualitative urgency levels ranging from low to very high (low, medium, high, and very high). Corresponding to the qualitative urgency levels are the numerical values (2, 4, 6, 8, respectively); the sites can also be assigned sub-values (e.g., 2.1, 3.0, 6.8, 7.2, 7.9, etc.). Each SC site will be classified into one level group and assigned an SI. The greater the need for enforcement at a SC site, the higher the SI value assigned to it. The SI value of each SC site will be determined based on the objective judgment of program manager or decision-maker.

For SC sites, the PI of each site is a function of UI and SI:

$$PI = f(UI, SI) \tag{4.8}$$

And PI might be computed as a weighted value of UI and SI:

$$PI = \omega_1 UI + \omega_2 SI \tag{4.9}$$

Where,

PI = priority index,

UI = urgency index,

SI = special requirements index, indicating the urgency for special enforcement.

ω_1 and ω_2 = weights on UI and SI, respectively.

Weights can be determined by program managers based on local context and needs.

Once every site in the enforcement site pool has been given a PI, the PR, SS, and SC sites should each be sorted by highest to lowest PI value. PI values can be assessed yearly after every long-term evaluation of the MPRE program. This assessment should be conducted yearly because the computation of PI requires sufficient collision data, but the fluctuation of collision data over a short-term period, such as a month, makes PI values unable to correctly identify problematic locations. As a result, the rankings of SP and SC sites currently in the enforcement site pool should be updated every year.

4.3 Enforcement Resource Scheduling

Many methods can be used to determine where and when MPRE resources (personnel, devices, and vehicles) should be dispatched, ranging from those that are completely random to those that use algorithms that target explicit quantified goals. This thesis proposed two methods for enforcement scheduling which generate deployment schedules in a random way and a deterministic way respectively.

4.3.1 Randomized Scheduling Method (RSM)

The present MPRE program in Edmonton gives enforcement operators the freedom to choose sites from a predetermined site list and decide the exact time for visiting a site, the deployment hours at the site, and the sequence of visiting these sites in one shift. To avoid disrupting the current enforcement culture, a randomized resource scheduling method is proposed to maintain the autonomy given to operators. The proposed random scheduling method is similar to the method used by the Random Road Watch (RRW) program in Australia (Leggett, 1997); however, unlike the RRW program, which aims to cover as many routes as possible by randomly allocating road segments in a weekly schedule, the proposed method targets sites shortlisted through the aforementioned site identification process. The randomized enforcement schedule also needs to comply with local enforcement policies, actual enforcement capabilities, and deployment guidance determined from historical data analyses.

Two main procedures are included in enforcement resource scheduling: the development of a monthly site list and the generation of a set of weekly deployment schedules.

4.3.1.1 Development of a Monthly Site List

An enforcement site list is to be developed monthly, based on the results of a monthly performance evaluation of the program (detailed information about the monthly evaluation will be discussed later). Two steps are involved in developing the monthly site list:

Step 1: Determine the Number of Sites in the Monthly Site List

The number of sites in a monthly site list should be determined based on the estimated enforcement resource availability over the coming month, including the number of available devices, personnel, and the actual enforcement capability, such as the number of sites that can be visited per shift.

In the CoE's current MPRE program, two shifts are scheduled each day for MPRE, with one squad assigned in each shift. As shown in Table 2, there are four PR squads in total, each of which has up to nine enforcement units (vehicle + device). According to program standards, at least two site visits are expected to be made by each enforcement unit per shift. Assuming there are four weeks (28 days) in a month and all enforcement resources are deployable, about 1,008 site visits can be made in one month. Historical deployment data for Edmonton indicate that, on average, a site is typically visited about four to five times per month; therefore, a minimum of about 201 to 252 sites can be included in a monthly site list. However, the actual deployment data show that three site visits can be achieved on average by one enforcement unit in one shift, which exceeds the minimum of two required. Thus, when all MPRE program resources are available, 1,512 site visits can be made in one month. As a result, approximately 302 to 378 sites can actually be enforced each month. Therefore, in order to make full use of the enforcement resources as well as ensure that the workloads are compatible with the enforcement capability, about 300 sites can be included in a monthly list, when resource availability is the same as the expected level.

Step 2: Determine the Proportion of Enforcement for Each Site Type

The majority of the candidate sites are PR sites, as PR sites are routine enforcement locations where speed issues have been confirmed and the sites are approved by the Edmonton Police Service for enforcement. At these locations, no additional examination of the feasibility of enforcement is required.

A review process necessary to approve sites for activation and enforcement usually takes five to 11 days. The lead time for the review process should be considered before adding a SS site to a monthly list. At the initial stage of implementing a new deployment strategy, a small percentage of SS sites are to be enforced each month. As increasingly more SS sites are approved over time, the percentage of SS sites can be increased gradually (Wang, Kim, & El-Basyouny, 2014a).

MPRE at SC sites are usually required due to the requests of government or third parties for the purpose of addressing special concerns or urgent problems. Depending on the average number of requested SC sites each month, there are two potential ways to determine the proportion required for each type of site (PR, SS, and SC) in the monthly site list (which includes 300 sites):

Scenario 1:

If there are only a small number of SC sites, all of them can be included in the monthly schedule. The number of PR and SS sites can be determined according to both a predetermined ratio and the number of sites that can be contained in the schedule in addition to the SC sites. For example, in addition to the SC sites, PR sites may take up 90% and SS sites may take up 10% in the monthly site list. If the number of SC sites in the month is 20, then the total number of PR sites and SS sites is 130 (150 minus 20). The number of PR sites is 117 (90% of 150) and the number of SS sites is 13 (10% of 150). However, given the urgent and random nature of SC sites, it is difficult to predict exactly how the total number of these sites changes from month to month.

Scenario 2:

If the number of SC sites is fairly large, only a portion is selected for the monthly list. Little information pertaining to how to decide the distribution of each site type in a site list has been found in previous literature. However, predetermined percentages can be assigned in pilot enforcement plans. For example, it can be assumed that the percentages of PR sites, SS sites, and SC sites are 70%, 10%, and 20% respectively. The exact percentages need to be further discussed and adjusted according to field conditions and program needs.

Step 3: Generation of a Monthly Site List

Once the total number of sites and the percentage of each site type to be included in the monthly list are determined, a monthly site list can be generated. Sites in the monthly site list are selected from the original site pool by site type, based on their PI values. Sites ranked successively may have identical or approximate values of PI, which means these sites have equivalent needs of enforcement. Therefore, for a specific site type, sites that are not within the range of monthly enforced sites but have approximate PI values similar to the last site selected for the monthly list are also treated as candidates for a monthly site list. Then each candidate is assigned a uniformly distributed pseudo-random number. All candidates are sorted by the random value from highest to lowest. The first 300 (as estimated in Step 1) sites are eventually included in the monthly site list.

The enforcement schedule is updated monthly, whereas PI values of sites do not change within the update cycle of PI, which is longer than one month (planned to be every season, half a year, or a year). Using PI values, the same list of sites is likely to be enforced every month. This monthly site list generation method ensures some variability in the list of sites to be enforced every month.

4.3.1.2 Development of a Weekly Deployment Schedule

To tailor the deployment schedule according to changing resource availabilities from week to week, the monthly site list is to be further divided into weekly site lists.

Step 1: Decide the Number of Visits at Each Site

Enforcement times at each site should be decided according to the PI value. More visits are required for sites with a higher PI value, while relatively few visits are needed for those with lower PI values. Sites are classified into different levels based on PI values before assigning visit times. However, due to the terms in the equation for calculating PI is different for each site group (PR, SS and SC), the work of classifying should be done for each site group separately. For sites at a specified level of a site type, deployment times at each site will be decided by generating a random integer within a predetermined interval range based on analysis results of historical deployment statistics.

For example, in Edmonton from April 2009 to March 2013, for sites being enforced at least once a month, the average deployment frequency is four to five times per site per month; the median is three times per month, while the mode is once per month. Particularly, a minority of sites were being visited with extremely high frequency (i.e., more than 30 times per month). Moreover, the monthly deployment frequency statistics show that one or two visits per site was achieved in 30% of cases, while the visits ranging from three to five took place in another 30% of cases. In 25% of cases, sites were enforced six to 15 times per month. For sites enforced 16 to 20 times and more than 20 times, each accounts for 5%. Therefore, except for sites with extremely high PIs, if each site type is classified into three levels, the visit times for Level 1, Level 2, and Level 3 can range between [6,10], [3,5] and [1,2], respectively. For those with extremely high PIs, the range can be set as [15, 20].

Step 2: Distribute Site Visits to Weekly Site Lists

After deciding visit times for each site, all visits are randomly distributed into weekly site lists made for every squad. For example, in Edmonton, when all four PR squads are available, 16 weekly site lists should be developed, and each PR squad has one list per week. The number of visits included in a weekly site list is tailored to the estimated enforcement capability of the corresponding squad. When developing the weekly site list, it is assumed that the enforcement resources and capability remain the same from week to week. If there are major resource availability changes among squads, enforcement tasks can be offloaded to other squads if possible.

Based on the weekly site list, the enforcement tasks are evenly divided into sub-lists for all available operator/enforcement unit combinations in the squad. If there is no change in the availability of enforcement units, the number of sub-lists for a squad will remain the same in the next week; otherwise, the squad leader can make adjustments to the sub-lists.

Step 3: Assign Vehicles to Operators

The work of assigning vehicles and devices to operators is done on a weekly basis. PR devices are fixed in enforcement trucks or vans, forming enforcement units. Sergeants will assign operators a unit at the beginning of each week. The relationship between the enforcement equipment unit and operators is one-to-many: one equipment unit will be operated by different operators during different shifts. Operators try to use the same unit each shift that they work within the week, unless the unit is unavailable.

When an enforcement unit is unavailable, the operator will request the sergeant to temporarily share equipment with another operator, if it is possible. If there is no change in the availability of enforcement units and (or) operator roster, then the vehicle and device assignment plan will be repeated in the next week.

Step 4: Generate Weekly Enforcement Schedules

The preliminary weekly enforcement schedule is made at the beginning of the week or the last day of the preceding week based on the operator's judgment and decision. The real enforcement schedule can be adjusted by the operator according to dynamic conditions.

The enforcement operators are given autonomy each week to make choices regarding which sites to visit on their sub-list, when, and in what order. Operators can be guided in these choices by factoring in site characteristics that were identified and compiled in the site identification process. Other site-specific information that may guide operators in their decisions may include collision peaks (daily and seasonal), daily and monthly distributions of speed violations, deployment history, and the mapped relationship between enforcement intensity and collision reduction. There are three rules that operators need to follow when making scheduling decisions. First, the same site cannot be enforced more than once per shift. Second, it is better to avoid a site being enforced more than once during a day, or in two contiguous shifts. Thus, when making decisions, operators within one shift should coordinate with each other, and the operators who take over for the PM shift need to refer to the schedules of the AM shift. Third, the time halo effect should be considered when operators decide the interval between two visits at the same site. Generally, the effect of MPRE lasts for three to four days, according to existing studies (Vaa, 1997).

Based on current deployment experience, the minimum and maximum deployment time lengths at a location are one and four hours, respectively. The minimum duration can be lowered according to specific deployment circumstances. During their shift, operators can move between sites, but will return to the OTS at the end of each shift.

4.3.2 Deterministic Scheduling Method (DSM)

In order to avoid overly disrupting the current enforcement culture of the CoE and make it easier for enforcement operators to accept a new deployment strategy, the RSM was developed so that it can be adopted in the initial program stage. However, it is expected that more controls will gradually be imposed in the program. Therefore, a scheduling method that imposes complete control on enforcement operators may prove to have some benefits over the previously introcuced scheduling method. Providing a set of constraints and a monthly site list that is developed using the methodology proposed in Section 4.3.1, the preliminary deployment schedules can be generated automatically. This will help to simplify the management of the MPRE program, and also reduce the operators' workloads.

A deterministic scheduling method (DSM) is proposed in this section. This DSM has been solved and tested by a numerical example. The results of this method were compared with the results of the RSM. The numerical test results of the DSM were used as benchmarks to assess the validity of the RSM described in Section 4.3.1.

4.3.2.1 Mathematical Formulation

The deterministic scheduling method provides a two-stage scheduling model. In the first stage, the deployment frequency at each site is decided by using an integer linear programming model. In the second stage, allocation and sequencing of deployment tasks are determined by using another integer linear programming model.

Stage 1: Determine Deployment Frequency

The integer linear programming optimization model is expressed as the following:

$$Z_1 = max \sum_{n=1}^{L} PI_n \, v_n, \tag{4.10}$$

Subject to:

$$\sum_{n=1}^{L} v_n \in [LB, UB], n \in L \tag{4.11}$$

$$lb_n \le v_n \le ub_n, \qquad \forall n \in L \tag{4.12}$$

Where,

L	the number of sites to be enforced
v_n	Predetermined monthly deployment times at site n
PI_n	Priority index value of site n
n,	Site index
LB, UB	The lower bound and upper bound of the total number of deployment times per month
lb_n, ub_n	The lower bound and the upper bound of the deployment times at site n per month

The objective of the model (4.10) is to maximize the sum of the PI values of the enforced sites. Constraint (4.11) stipulates the maximum range of the total number of deployment times during the month. Constraint (4.12) restricts the number of enforcement times at a particular site.

Stage 2 Allocate Site Visits to Shifts

The integer linear program generates the weekly enforcement schedule on a per-shift basis.

The indices and variables include the following:

L	The total number enforcement sites
S	The total number of shifts
D_{mn}	Travel distance between site m and n

M_s	The set of sites enforced in shift $(s-1)$; $M_s = \begin{cases} \emptyset, \text{if } s = 1 \\ \{i_{s-1}, j_{s-1}, k_{s-1}\}, \text{if } s \geq 2 \text{ and } s \in S \end{cases}$
DT_n	The number of actual deployment times at site n in a month
V_{n_s}	The number of deployment tasks left at site n before shift s
n, m	Site index, $n \in L$, and $n \in N_+$
i, j, k	Site index; i, j, and k represent the first, the second, and the third site enforced within one shift; $i, j, k \in L$, and $i, j, k \in N_+$
s	Shift index, $s \in S$, and $s \in N_+$
α	The coefficient of PI. In this numerical example

The decision variables are these:

u_{mn}	A binary variable that equals 1 if site n is visited after site m; 0 otherwise.
C_{i_s}	A binary variable that equals 1 if $V_{i_s} > 0$,and $PI_i = max_{\substack{n \notin M \\ n \in L}} PI_n$, and $D_{ki} > 1$, where site n is the first site being enforced in shift s, and site k_{s-1} is the last site enforced in preceding shift $(s-1)$; 0 otherwise.

The mathematic model is as follows:

$$Z_2 = \min_{\substack{j \notin \{i_s\} \cap M \\ k \notin \{i_s, j_s\} \cap M}} \sum_{s=1}^{S} C_{i_s}\left[u_{ij}\left(D_{ij} + \alpha PI_j\right) + u_{jk}\left(D_{jk} + \alpha PI_k\right)\right] \tag{4.13}$$

Subject to:

$$V_{n_s} > 0, n = i, j, k \quad \forall s \in S \tag{4.14}$$

$$DT_n \leq V_{n_1}, \qquad \forall n \in L \tag{4.15}$$

$$\sum_{j \notin \{i_s\} \cap M} u_{ij} = 1 \tag{4.16}$$

$$\sum_{k \notin \{i_s, j_s\} \cap M} u_{jk} = 1 \tag{4.17}$$

$$DT_n, V_{n_s} \in N \tag{4.18}$$

The objective defined in equation (4.13) is to minimize the sum of the weighted distance and PI among the three sites in a shift. Site i is first enforced in shift s. Starting from the second shift, the first site has the highest PI value, and the distance to the third site visited during shift $(s-1)$ is greater than the minimum distance to account for a distance halo effect. In this example, we have arbitrarily chosen this minimum distance to be one kilometre. The second enforced site j in shift s should not only be located close in distance to site i but also have a high PI value. Which site will be enforced second depends on a combined weighted value of travel distance and PI. The third location (site k) in shift s is selected using the same method. Constraint (4.14) ensures the number of remaining deployment tasks at sites chosen to be enforced in shift s is equal to or greater than one. Constraint (4.15) ensures the actual number of enforcement visits to a site in one month is equal to or less than the maximum number required, which was determined in Stage 1. Constraint (4.16) stipulates that only one site is enforced right after the first site i in shift s, and the site has neither been visited in the last shift nor been visited as the first site in the current shift. Constraint (4.17) ensures only one site is visited in shift s. The site is neither the same location as any site visited in the last shift nor the same as the first two sites in the current shift. Constraint (4.18) restricts the actual number of deployment visits to site n in the month, and the number of the remaining tasks at site n before shift s is a non-negative integer.

4.3.2.2 Algorithm

The integer linear programming problem in the Stage 1 can be solved easily using the solver feature in Microsoft Excel 2010. To solve the mixed integer programming problem in Stage 2, the model is imbedded in an algorithm. The algorithm is as follows:

1. Import basic information including site ID, PI values, predetermined deployment frequency, and the travel distance between every two sites;

2. Initialize the sum of the weighted travel distance and PI for each pair of sites as zero, $TDP_{ij} = u_{ij}\left(D_{ij} + \alpha PI_j\right)$;

3. Initialize the set of sites being enforced before the current shift $M_s = \emptyset$;

4. For $n = 1, \dots, L$:

5. For $\mathrm{s} = 1, \dots, S$:

(1) Find the first site i in shift s:

- If $s = 1$, then $i = n$; the number of enforcement tasks remaining at site i before the next shift is one less than the number before the current shift, $V_{i_s} = v_i - 1$;

- If $s \geq 2$, given the constraints that $V_{i_{s-1}} \geq 1$, $i \notin \{i_{s-1}, j_{s-1}, k_{s-1}\}$, the site that is more than 1 km away from the last site (k), in shift $(s-1)$, and has the highest PI value will be the first site (i) in shift *s*; Reduce the number of deployment tasks at site *i* before the current shift by 1, $V_{i_s} = V_{i_{s-1}} - 1$;

(2) Find the second site j in shift s:

- Calculate TDP_{ij}, j =1,…,L; Sort TDP_{ij} in ascending order;

- For the site with minimum TDP_{ij}, if $V_{j_{s-1}} \geq 1$ *and* $j \notin \{i_{s-1}, j_{s-1}, k_{s-1}, i_s\}$, then site j is the second enforced site in shift s; $V_{j_s} = V_{j_{s-1}} - 1$;

(3) Find the third site k in shift s:

- Calculate TDP_{jk}, k =1,…,L. Sort TDP_{jk} in ascending order;
- For the site with minimum TDP_{jk}. If $V_{k_{s-1}} \geq 1$ and $k \notin \{i_{s-1}, j_{s-1}, k_{s-1}, i_s, j_s\}$, then site k is the third enforced site in shift s, $V_{k_s} = V_{k_{s-1}} - 1$;

(4) Update $M_s = \{i, j, k\}$;

6. If all shifts ($s = 1 \dots S$) have been assigned enforcement tasks, then return back to Step 3 to change the current starting point and continue the simulation; If not, repeat from Step 4;
7. If all sites ($n = 1 \dots L$) have been set as the starting point, then output all feasible schedules and stop; if not, return back to Step 3 and continue the simulation.

4.4 Guidelines for Evaluation and Program Adjustment

Program evaluations will be performed to measure program efficacy and efficiency, as well as to provide inputs for site identification and guidance for adjustments to enforcement resource scheduling.

4.4.1 Short-Term Evaluation

The purpose of the short-term evaluation is to continually monitor the program performance and make necessary adjustments.

4.4.1.1 Evaluation Timeframe

The program evaluation will be conducted on a monthly basis. The purpose of the monthly evaluation is to facilitate adjustments to the monthly site list and deployment strategies. A monthly evaluation frequency is chosen for short-term evaluation because both weekly and yearly evaluations cannot meet the requirements. A weekly evaluation is too short to provide meaningful information based on the desired statistics; however, a yearly evaluation is seen as too infrequent for use in making program adjustments to, for instance, updating site information. Moreover, the photo radar enforcement programs in other jurisdictions have also taken one month as the frequency for short-term evaluation (Newstead, Cameron, & Narayan, 1998; Tay, 2010).

An evaluation can be scheduled in the last week of the month to assess the month's program performance. It is assumed that the data analysis and evaluation will be completed within the last week. This time can be adjusted according to the extent of the analysis required and available resources.

4.4.1.2 Evaluation Criteria

The evaluation results should provide information for refining the program design, changing the candidate site list, and adjusting deployment strategies. The short-term program performance can be evaluated from two main aspects, each involving specific performance measures:

1. Deployment-related statistics

    - The number of sites enforced monthly
    - The deployment frequency per site each month
    - The deployment length per site visit in the month
    - Spatial distribution of the enforced sites

- Hourly distribution of deployment intensity
- Utilization of both vehicle and personnel resources
- Compliance with the enforcement schedule (Newstead, Cameron, & Leggett, 1999)

2. Effect on the number of speed violations
   - The number of speed violations detected per site visit per month (Leggett, 1997)
   - Time distribution for speed violations (hourly or weekly level)

4.4.1.3 Short-Term Adjustment

It is difficult to observe significant changes in the number of collisions in a short-term analysis; therefore, changes in the number of speed violations are used as proxies for performance measures from month to month. The monthly adjustment to the candidate site list will be based on changes in speed violations, resource availability, and enforcement capability.

For PR sites and SS sites, sites with non-decreasing speed violations are retained in the monthly site list. Sites with decreasing speed violation numbers can be replaced by sites selected from the site pool with high PI values.

For SC sites, the sites with continually significant speed violations, or those that are still in demand of enforcement due to special needs should be retained. If the special requirement has been met or a significant speed violation reduction (i.e., compared with numbers from three months prior) has been observed, the site can be removed from the list. More sites can be included in the monthly site list if more enforcement resources are added, as long as the total number of sites is in line with estimated resource availabilities for the subsequent month.

The total number of sites and the percentage of each type of site in the candidate site list can be reset based on the monthly evaluation results and the number of specially requested sites in the site pool.

4.4.2 Long-Term Evaluation and Adjustment

As some performance measures are not meaningful if assessed at monthly frequencies, a long-term evaluation is also required.

4.4.2.1 Evaluation Timeframe

The long-term evaluation can be performed at six-month, nine-month, or twelve-month intervals, depending on specific needs and constraints (Newstead, Cameron, & Leggett, 1999). The long-term evaluation can be conducted during the first week of the last month of a year. When short-term and long-term evaluations are scheduled to be performed concurrently in a month, the work involved in the short-term evaluation can be combined into the long-term evaluation.

4.4.2.2 Evaluation Criteria

The long-term evaluation consists of an assessment of city-wide collisions and speed data, as well as statistics collected through MPRE deployment. The long-term program evaluation should consist of three analyses:

1. Assessment of changes in collisions at both city-wide and site-level

The number of collisions has a negative relationship with the operational level of enforcement (Elvik R. , 2001). To examine and verify the statement, the changes in collisions in terms of frequency, severity (i.e., fatal, injury, PDO), and type (i.e., followed-too-close, ran-off-road, etc.) versus yearly deployment operating hours (Newstead & Cameron, 2003) and detected speed violations (Cameron & Delaney, 2006; Diamantopoulou & Cameron, 2002) should be investigated separately at both the city-wide and enforcement-site level. In addition, the monthly and seasonal time distribution and geographical distribution of collisions should be investigated.

2. Assessment of speed violations

The changing trend in the number of speed violations should be analyzed. The geographical distribution and time distribution (i.e., daily, monthly, and seasonal) of detected speed violations need to be studied at both enforced and non-enforced locations.

3. Assessment of changes in speed

The speed changes needed to be examined include reduction in the mean and 85th percentile speeds at enforced and non-enforced locations (Newstead, Cameron, & Leggett, 1999), compliance to the speed limit, and travel speed variance at enforced sites (Newstead, Cameron, & Leggett, 1999).

4. Assessment of program operating costs and revenue generation

The program costs include collision costs, violation processing and ticket reviewing costs, and peace officer operating costs (Leggett, 1997). The program benefits can come from savings from reduction in collision severity, the number of collisions and speed violations, as well as the fine revenue from issuing tickets.

4.4.2.3 Long-Term Adjustment

After the long-term evaluation, the enforcement site pool will be updated. Based on the collision records, new locations will be identified and added to the pool. A comparison between the geographical distribution of sites currently in the site pool and city-wide collisions and speed violations over the past year will illustrate which new locations should be included in the site pool. However, SC sites can be added to the site pool or a monthly site list whenever special enforcement is requested. Sites experiencing a continuous significant reduction in both collisions and speed violations can be deactivated but still retained in the pool. More details related to both the short-term and long-term evaluations will be mapped out for the pilot study program as well as for implementation of the program design.

4.5 Conclusion

The program design is based on historical data available from April 2009 to March 2013. The priority-based site selection process for MPRE is used to identify high-risk locations for speeding by using a multi-variable priority index computation method. The monthly enforced sites are randomly selected from sites with high-priority index values in accordance with estimated monthly enforcement capability and resource availability. In keeping with the existing enforcement culture and institutional structure, the RSM allows the operators to make weekly deployment decisions. In addition, randomness is built into the program at several levels with the expectation that it will help maintain a perception of randomness to drivers. A DSM is developed as an alternative to the RSM to demonstrate how a more centrally controlled scheduling program may compare to the RSM. It can also serve as a benchmark for assessing the RSM. A short-term evaluation plan is proposed in order to provide inputs for updating the monthly site list, while long-term evaluation can provide feedback on overall program performance and adjustments to the enforcement site pool. The proposed enforcement-evaluation-adjustment process provides a mechanism for program refinements to be informed by program performance evaluation results.

CHAPTER 5. NUMERICAL EXAMPLE AND SIMULATION RESULTS

In this chapter, the methodology for mobile photo radar enforcement (MPRE) scheduling and deployment, which was proposed in Chapter 4, is demonstrated and tested in a small-scale example, generating a two-week schedule. Sites selected from a small sample area within the City of Edmonton (CoE) were used as the potential enforcement site pool. A month-long site list was generated by applying the procedures proposed in Chapter 4. Since enforcement schedules can be generated on a weekly basis, only the first two weeks' enforcement schedules (rather than the entire month) were developed to illustrate the enforcement schedule generation process using the randomized scheduling method (RSM) and the deterministic scheduling method (DSM) proposed in Chapter 4. The performance of each method was evaluated based on three performance measures (total travel distance, sum of PI, and expected violation coverage).

5.1 Problem Statement and Assumptions

To demonstrate the methodology of MPRE scheduling and deployment proposed in Chapter 4, two weekly schedules were generated. The dataset for this example was taken from the same dataset described in Chapter 3 (the CoE, April 2009 to March 2013). Due to the fact that this example is a scaled down illustration of the scheduling methodology in Chapter 4, the context was simplified using the following measures. Firstly, a small sample of sites was chosen from the entire enforcement site pool throughout the CoE by placing a polygon on a section of the city. Secondly, special consideration (SC) sites were not considered and only the photo radar (PR) and speed survey (SS) sites were used. Thirdly, weekly schedules were generated only for the first two weeks rather than for the entire month. However, it is important to note here that deployment frequency at each site was planned for an entire month. Several other assumptions made to scale back the size of this example were made, and will be mentioned in the proceeding paragraphs. The following assumptions pertaining to the staffing level were made:

1. Two squads take charge of the MPRE tasks in the selected area, and they take turns enforcing;
2. Only one squad carries out enforcement within one shift;
3. Each squad dispatches one enforcement unit for every shift;
4. A month consists of four weeks (28 days);
5. Two shifts are arranged every day for covert MPRE;
6. Three sites are visited per shift.

Based on these assumptions, the total number of deployment times should be 168 per month (168times=28 days ×2 shifts per day ×3 site visits per unit per shift ×1 unit per shift). In reality, the enforcement capability and resource availability may change. To ensure sufficient numbers of deployments are planned to make full use of the enforcement resource if the enforcement capability and resource availability increase, the total enforcement times scheduled in a month should be a bit higher than the estimated number. To better imitate reality, when planning the number of monthly deployment times in the simulation, it is acceptable as long as the number is between 168 and 180, rather than exactly 168 times. But when generating weekly schedules, it is assumed that the staffing level remains constant from week to week, which means that 84 (half of 168) deployments can be scheduled in the first two weeks, no matter how many deployment times are planned for the month.

5.2 Illustration of Randomized Scheduling Method

5.2.1 Site Identification

A sample set of sites in North Edmonton was selected because this area of the city contains sites located on a variety of roadway types. Forty PR sites and 40 SS sites were included within the polygon. These 80 sites comprised the candidate site pool for the numerical example. Among the PR sites, the number of sites located on arterials, collector roads, and local roads were 24, 14, and 2, respectively; the numbers were 12, 14, and 14 for SS sites, respectively. The collision and violation data from April 2009 to March 2013 (introduced in Chapter 3) were used for computing each site's priority index (PI).

Step 1: Normalize Collision and Speed Violation Data

The collision and speed violation data were normalized for PR sites and SS survey sites respectively by road type. Only when a vehicle's speed exceeds the speed limit to a certain degree (speed tolerance) can the photo radar system be triggered so that the speeding behaviour will be identified as a speed violation. For SS survey sites, although speed data was collected at each site during the survey periods and the information on facility speed limits can be acquired, the accurate number of speed violations cannot be calculated due to the speed tolerance varying by time and location. Hence, only collision data were used for computing PI. For PR sites, 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. Table 7 shows the data used for collision and speed violation normalization.

Table 7 Data for Collision and Speed Violation Normalization

		PDO		Injury		Fatal		Violation	T (hours)	Violation/T
		PR	SS	PR	SS	PR	SS	PR	PR	PR
Arterial Road	max	36	46	7	9.5	0	0	15838	1773.2	8.9
	min	0	2	0	0	0	0	0	2	0
Collector Road	max	9.5	26	2	5	0	0	3801	603.3	6.3
	min	0	0	0	0	0	0	0	5.4	0
Local Road	max	3	10.5	1	1	0	0	1	18.2	0.05
	min	3	0	0	0	0	0	0	18.9	0

Step 2: Calculate PI for each site

As explained in Chapter 4, for PR and SS sites, $PI = UI$, which represents the degree to which enforcement is needed at the site due to speeding and safety concerns. The coefficients of variables relating to collisions at different severity level ($\alpha_F, \alpha_I, \alpha_P$) were calculated based on the direct collision costs. The direct collision costs are taken from a collision cost study of the Edmonton Capital Region Area in 2007 (De Leur, 2010). The probabilities of an injury collision and a fatal collision resulting from excessive speed, which were needed for calculating the coefficient value of speed violation (β), were referred in the results of a study in Spain (Ayuso, Guillén, & Alcaniz, 2010). The data for computing the coefficients and the values of the coefficients are shown in Table 8. The PI values of all 80 sites in the candidate site pool are shown in Table 15 in the Appendix.

Table 8 Data for Computing Coefficients and the Calculation Results

	Direct Cost per Collision	**Probability of Collision resulting from Speeding**	**Coefficient Value**
Fatal Collision	$181,335	0.87	$\alpha_F = 16.6$
Injury Collision	$39,524	0.13	$\alpha_I = 3.6$
PDO Collision	$10,902	N/A	$\alpha_P = 1$
Speed Violation	N/A	N/A	$\beta = 5.3$

5.2.2 Monthly Site List Generation

Step 1: Determine the Number of Sites in the Monthly Site List

Based on the assumed staffing level, 168 deployment times can be scheduled in one month. The historical deployment statistics collected from the CoE show that the enforcement times at some sites were zero per month, which means these sites were not in the enforcement list for that month. Excluding those non-enforced sites, the median deployment frequency per site was four times per month, implying that 42 sites can be enforced in a month. Therefore, it was decided that 40 sites would be included in the monthly list.

Step 2: Determine the Proportion of Each Site Type

SS sites need to be approved before becoming a new enforcement site. The approval process usually takes five to 11 business days as mentioned in Chapter 3. However, since PR sites are routine enforcement locations in the COE's current MPRE program, the sites' feasibilities have already been checked and as such can be immediately included in the monthly list. At the initial stage, the PR sites should make up a larger proportion of the total sites than SS sites in the monthly list. As more SS sites are approved, the proportion of SS sites can be increased. In this example, it was assumed that 75% of sites were PR sites and 25% SS sites, resulting in 30 PR and 10 SS sites in the monthly list.

Step 3: Generating a Monthly Site List

For the 80 sites in the candidate site pool, information including site ID, site type (PR or SS), road type, and *PI* value are shown in Table 15 in the Appendix. As illustrated in Table 15, the *PI* values for the top 30 PR sites ranged from 1.2 to 18.5. Because the *PI* value of the 31st PR site (1.1) was very close to the 30th site, the top 31 sites were candidates, from which 30 PR sites were selected. Similarly, the *PI* values of the SS sites ranked at 10th and 11th were 2.61 and

2.56, respectively. The 10 SS sites in the monthly list were selected from the top 11 sites. PR sites and SS sites were selected from the candidate site pool by applying a randomized method. Each candidate was assigned a value chosen randomly from a uniform distribution between zero and one. Based on these assigned random values, the first 30 PR sites and the first 10 SS sites were chosen for the monthly site list. Table 9 presents information about each site chosen for the monthly schedule. The monthly site list was used as input for the simulations of different scheduling methods. The simulation results will be given in Section 5.3.

Table 9 Monthly Site List

Site ID	Site Group	Road Type	PI	Site ID	Site Group	Road Type	PI
1	SS	C	4.45	21	PR	A	4.58
2	SS	A	4.26	22	PR	C	4.24
3	SS	A	4.03	23	PR	A	4.06
4	PR	A	18.55	24	PR	C	3.82
5	PR	C	9.11	25	PR	C	3.70
6	PR	L	8.90	26	PR	A	3.65
7	PR	C	8.51	27	PR	A	3.54
8	PR	C	8.17	28	PR	A	3.23
9	PR	A	7.21	29	PR	C	3.01
10	PR	A	6.57	30	PR	A	2.96
11	PR	A	5.77	31	PR	A	2.55
12	PR	A	5.61	32	SS	L	2.80
13	PR	A	5.49	33	SS	L	2.61
14	PR	C	5.25	34	SS	A	2.56
15	PR	A	5.18	35	PR	A	2.02
16	PR	A	5.02	36	PR	C	1.95
17	SS	A	3.82	37	PR	A	1.77
18	SS	L	3.60	38	PR	A	1.30
19	SS	L	3.60	39	PR	A	1.21

5.2.3 Weekly Schedule Generation

Step 1: Decide the Number of Visits at Each Site per Month

The simulation operated in place of the squad leaders being able to make informed decisions on how frequently a site should be visited. As stated in Chapter 4, PR sites and SS sites were classified into different levels according to their PI values. The highest PI value (18.5) within the PR sites was far larger than the next highest PI (9.1), indicating that this site deserved a specifically high deployment frequency. Historical deployment data show that the monthly deployment frequency for the top 2.5% (one site is 2.5% of 40) of sites could range from 40 to 70 times. However, these statistics were based on the actual staffing level that five to eight enforcement units were deployed together within one shift (as shown in Table 2 in Chapter 3). Since only one unit was assumed to carry out enforcement in one shift, the monthly deployment frequency of these sites with particular high requirements could be considered between eight and 14 times (if five units were deployed together in reality) or five to nine times (if eight units were deployed together in reality). In this example, it was decided that the monthly deployment times at such sites ranged between [9, 14]. For the rest of the PR and SS sites, they were classified into three levels respectively. The range of enforcement times is [6, 10] for Level 1, [3, 5] for Level 2, and [1, 2] for Level 3. The monthly deployment frequency at each site was chosen by generating an integer that is uniformly distributed within the range of the corresponding level. The number of deployments at each of the 40 sites is presented in Table 10. In total, 180 site visits were pre-arranged for the month.

Table 10 the Deployment Frequency of Each Site in the Monthly Site list

Site ID	MDF*	Site ID	MDF*	Site ID	MDF*	Site ID	MDF*
1	7	11	8	21	4	31	4
2	8	12	7	22	3	32	1
3	8	13	7	23	3	33	1
4	10	14	6	24	4	34	2
5	6	15	7	25	3	35	2
6	6	16	8	26	3	36	1
7	6	17	4	27	4	37	1
8	6	18	4	28	4	38	2
9	8	19	3	29	4	39	1
10	6	20	3	30	3	40	2

*MDF means monthly deployment frequency

Step 2: Distribute Site Visits to Weekly Site Lists

Since a month was assumed to have four weeks and two enforcement units took turns to do enforcement, eight weekly site lists should be generated. Assuming the enforcement capability of each squad is the same, a weekly schedule should include 21 site visits, given 168 deployments were able to be supported by the assumed staffing level.

Each visit was randomly assigned a week index, which ranges from one to eight, where one and two represent the site lists for Squad 1 and Squad 2 in the first week, respectively. Three and four represent the site lists for Squads 1 and 2 in the second week, and so on. Because the number (180) of deployments for a month was greater than the number (168) that could be achieved by the assumed staffing level, more than 21 deployments might be assigned to one week. In order to evenly distribute enforcement tasks to the eight weekly site lists, a preliminary weekly list could include 20 to 24 deployment tasks. The number of deployment tasks assigned to each of the eight weekly lists is shown in Table 11. The deployment times for each weekly site list were found to be greater than 21. Under such circumstances, it was assumed that the enforcement operator would make decisions to choose 21 enforcement tasks from the excessive assigned tasks in the next step (Step 3). Because it was assumed that each squad had only one enforcement unit each, the weekly site list for a squad was also simply the list for each unit.

Table 11 Number of Deployments in the Weekly List

Week	Weekly list ID	Squad ID	Deployment Times
1	1	1	22
	2	2	22
2	3	1	22
	4	2	22
3	5	1	22
	6	2	24
4	7	1	24
	8	2	22

Step 3: Generate the Weekly Enforcement Schedule

Based on the weekly site list, the deployments were allocated in a weekly schedule by referring to the level to which a site belonged and the site's geographical location on the map. These decisions were assumed based on enforcement operators' judgments from experience and firsthand knowledge about what was happening at these sites.

Sites with high PI values were given higher priorities than the sites with lower PI values to be arranged in weekly schedules. The low PI value sites were more likely to be excluded from a weekly schedule when excessive numbers of enforcement tasks were assigned for the week. When creating weekly schedules, three rules should be followed:

1. A site can be enforced only once during a shift,

2. Sites enforced within the same shift should be close in distance to one another. However, sites located at a single location but for opposite directions of traffic should not be included in the same shift.

3. A site cannot be visited in two sequential shifts.

Five sets of feasible weekly schedules were generated for the first two weeks of a month. The details of the schedule will be discussed in Section 5.3 and 5.4.

5.3 Simulation Results

5.3.1 Results of Randomized Scheduling Method Example

Based on the monthly site list presented in Section 5.2.2 and the procedures described in Section 5.2, five two-week schedules were generated based on the anticipated decisions of enforcement operators which were simulated by the author of the thesis. It is understood that this is a less-than-desirable procedure to generate a simulation of RSM. However, it is still necessary to gain some basic intuition about how the RSM could potentially perform, until a pilot test of the RSM can be done (see Section 5.4).

Since the number of predetermined weekly tasks exceeded the weekly enforcement capability, the site with lower *PI* value or location far away from other sites had the priority to be excluded in the weekly schedule. The weekly schedules developed by using the RSM for the first two weeks of the given month are shown in Table 16 in Appendix.

5.3.2 Results of Deterministic Scheduling Method Example

The deterministic scheduling simulation was executed based on the monthly site list presented in Section 5.2.2.

Firstly, the integer linear programming problem in Stage 1 was solved using the solver feature in Microsoft Excel 2010. The total number of deployment times per month was assumed to range from 168 to 180, which was the same as the constraint made for RSM. As for the number of deployment times at a particular site per month, because the median of deployment frequency is three, according to historical deployment data, the lower bound was set as three. In this example, since only one enforcement unit can be deployed in one shift, as explained in Section 5.2.3, the upper bound was set as 14.

The optimal monthly deployment frequency for each site is shown in Table 12. Most enforcement was planned to be deployed at sites with high *PI* values. Enforcement times of the majority of the sites were equal to the lower bound of the constraint on deployment frequency.

Table 12 Optimal Results of Deployment Frequency for Each Site

Site ID	Deployment Frequency	Site ID	Deployment Frequency	Site ID	Deployment Frequency	Site ID	Deployment Frequency
1	3	11	3	21	3	31	3
2	3	12	3	22	3	32	3
3	3	13	3	23	3	33	3
4	14	14	3	24	3	34	3
5	14	15	3	25	3	35	3
6	14	16	3	26	3	36	3
7	14	17	3	27	3	37	3
8	14	18	3	28	3	38	3
9	8	19	3	29	3	39	3
10	3	20	3	30	3	40	3

The results of Stage 1 were used as inputs of the mixed integer linear programming model in Stage 2. The optimization model of Stage 2 was solved by implementing the algorithm in MATLAB R2011a. In this example, the relative weight value of PI (α) was arbitrarily decided as -1.1. In total, the number of decision variable u_{mn} is 1560 (40×39), and the number of decision variable C_{i_s} is 40 when $s = 1$, and 36 when $s \geq 2$.

By changing the first site in the first visit, forty sets of two-week schedules were generated. With respect to the value of the objective function, the best five schedules were selected to compare with the results of the randomized method. The schedules are presented in Table 17 in the Appendix.

5.3.3 Performance Measures

In order to assess the comparative performances of both the RSM and DSM, the schedules generated by each method were evaluated using three performance measures: total travel distance between sites, total PI, and potential violation coverage.

1. Total travel distance between sites (TTD)

The travel distance (in kilometres) of each shift was calculated based on the sequence of enforced sites. It was computed using equation (5.1).

$$TTD = \sum_{s=1}^{S} D_{ij} + D_{jk} \tag{5.1}$$

It was the sum of the distance between the first site and the second site and the distance between the second site and the third site. The total travel distance was the sum of the distance of travelled in all shifts, excluding the distance from and back to the Office of Traffic Safety (OTS). Because it was assumed that the two squads took turns going out for shifts, the distance between the third site and the first site in two successive shifts was not accounted for in the total travel distance.

2. Total PI (TPI)

This measure was used to investigate how much attention was planned to give to locations with high enforcement priority. The value was computed by using the equation (5.2):

$$TPI = \sum_{i=1}^{L} PI_i DT_i \tag{5.2}$$

3. Violation Coverage (VC)

It was assumed that the number of hourly speed violations can be approximated by a uniform distribution (Iswanjono, Budiardjo, & Ramli, 2011). The number of hourly speed violations that occurred at sites with different road types was estimated based on the historical speed violation data of all sample sites, from April 2009 to March 2013. For sites located on arterials, collector roads, and local roads, the uniformly distributed number ranged between [5, 31], [3, 9], and [0, 1] respectively. The lower bound of the range was the average number of speed violations for the particular road type, while the upper bound was the maximum number of speed violations for the road type. The expected number of speed violations per hour at a site was predicted by using a uniform distribution random number generator.

The expected number of speed violations at each site per hour is presented in Table 13.

Table 13 Expected Speed Violations at Each Site

Site ID	Site Group	Road Type	Violations	Site ID	Site Group	Road Type	Violations
1	SS	C	7	21	PR	A	14
2	SS	A	28	22	PR	C	6
3	SS	A	8	23	PR	A	8
4	PR	A	26	24	PR	C	9
5	PR	C	8	25	PR	C	7
6	PR	L	1	26	PR	A	16
7	PR	C	5	27	PR	A	28
8	PR	C	4	28	PR	A	22
9	PR	A	9	29	PR	C	3
10	PR	A	29	30	PR	A	12
11	PR	A	29	31	PR	A	10
12	PR	A	23	32	SS	L	1
13	PR	A	28	33	SS	L	0
14	PR	C	3	34	SS	A	7
15	PR	A	29	35	PR	A	31
16	PR	A	17	36	PR	C	4
17	SS	A	9	37	PR	A	17
18	SS	L	1	38	PR	A	14
19	SS	L	1	39	PR	A	29
20	SS	A	17	40	PR	C	3

It was assumed that the effective enforcement time in a shift was evenly distributed to the three sites. As stated in Chapter 3, excluding the time for travelling from and back to OTS, which is about one hour for each, the effective enforcement time is about eight hours in a ten-hour shift. Therefore, each site visit could take approximately 2.67 hours. The potential violation coverage at a site within the two-week planning horizon can be computed by the following equation (5.3):

$$VC = \sum_{n=1}^{L} 2.67 \cdot DT_n \cdot Vio_n \tag{5.3}$$

Where,

DT_n the actual deployment times at site i

Vio_n the predicted hourly speed violation numbers at site i

5.3.4 Performance Assessment

Among the 40 schedules generated by the DSM, the best five schedules in terms of the objective function value (Z_2) were used for evaluating the performance of this method and comparing with the RSM. The performance measures' values of the schedules are shown in Table 14. Compared with the RSM, the DSM is better at minimizing the travel distance and, at the same time, addressing more high priority sites with limited deployment times. The RSM is potentially able to capture more violation than the DSM.

Table 14 Performances of Randomized Scheduling Method (RSM) and Deterministic Scheduling Method (DSM)

RSM	**Schedule**	TTD	TPI	VC
	1	138.35	513.14	3105.21
	2	128.45	513.14	3105.21
	3	117.8	513.29	3065.16
	4	121.95	514.66	3038.46
	5	150.6	510.79	2987.73
	Average	131.43	513.004	3060.35
	Variance	174.98	1.94	2450.20
DSM	**Schedule**	TTD	TPI	VC
	1	112.3	838.496	2093.28
	2	112.3	838.496	2093.28
	3	115.65	835.528	2015.85
	4	115.9	835.582	2058.57
	5	116.4	835.464	2090.61
	Average	114.51	836.713	2070.32
	Variance	4.14	2.65	1142.76

5.4 Discussion

The schedules made using the RSM resulted in a better variety of sites enforced in the first two weeks. As shown in Table 16 and Table 17 (in the Appendix), the five schedules created using the RSM covered 31, 31, 32, 32, and 31 sites, respectively, among the 40 sites, while the deployments were mainly distributed to 8, 8, 9, 9, and 9 different sites in the five schedules generated using DSM. The principle behind the RSM is to uniformly distribute the deployment tasks at sites to each week. Thus, the weekly enforcement is more likely able to cover more different sites. The weekly deployment times of a site ranged from [1, 5]. As for the DSM, It was observed that the enforcement mainly targeted only on a small number of sites that had high PI values. Enforcement would not be arranged at other sites unless all enforcement tasks at these sites were completed. The reason is that the principle behind the DSM is to give higher priority for the high PI sites. More deployment times tend to be assigned to sites with high PI values, and deployments at these sites are likely arranged at an early time on a schedule. In this numerical test, the predetermined enforcement times at each site were calculated in terms of the requirement of the whole month, but the schedules were only made for the first two weeks. If the four schedules for the whole month are generated using the DSM, enforcement should be shown to cover more sites during the second half of the month.

In terms of travel distance, Table 14 has shown that the DSM can create schedules resulting in shorter total travel distance than the RSM. The travel distance per shift in the schedules was checked. The results revealed that the travel distance per shift in the five schedules created using the RSM ranged between [2.45, 5.9] with a mean of 4.08, and the corresponding results of the DSM were [1.7, 9.9] with a mean of 4.70. In the schedules generated using the RSM, the variance of travel distance per shift is greater than that of the DSM. This difference is mainly due to the fact that the deployment sequence in a shift is decided by enforcement operators. Since their decisions are made shift by shift, it is highly possible that one site could have been ignored while all the other nearby sites have been enforced; therefore, this site has to be arranged to be enforced together with sites that are farther away from it. Moreover, the performance result of travel distance did not include the distance from and back to the OTS. But when enforcement operators make decisions on the deployment sequence for a shift, they consider the preferred overall travelling route, which starts from the OTS, passes the three sites, and ends at the OTS. However, for the DSM, the sequence is based only on the weighted sum of the travel distance and PI value, rather than the travelling route.

It appears unintuitive that the DSM has better coverage of high PI sites, but covers less speed violations than the RSM. However, this is caused by the present method of computing PI and predicting speed violations. The calculation of PI for PR sites combined the risks resulting from both collisions and speed violations, but the PI of SS sites only considered the historical collision data because the violation data was not available at the current stage. The number of expected speed violations for PR and SS sites was predicted based on the same statistical model. In the two-week schedule made by the DSM, the eight (or nine) sites included in the schedule were all PR sites. In contrast, both PR and SS sites were covered by the two-week schedule created by the RSM. Therefore, when evaluating the two scheduling methods with respect to the expected violation coverage (VC), the speed violations predicted to happen at SS sites contribute to the value of this performance measure for the RSM. In other words, no matter whether to take the RSM or DSM, the more amount of SS sites a schedule includes, the higher value of VC is resulted in.

However, it is not appropriate to conclude that the RSM is better than the DSM by looking at the violation coverage (VC) results alone. Both the VC and TPI account for the impact of the number of speed violations. TPI_is a hybrid performance measure which considers the impacts of not only the speed violations but also the collisions at each severity level and road type; however, VC only considers speed violations. Whether the VC or TPI can better reflect the effectiveness of the scheduling method in addressing speeding issues is not known. In addition, the objectives of MPRE include increasing both general and specific deterrence, and consequently improve road safety by reducing traffic collisions. High violation coverage potentially may increase specific deterrence, since it is likely that more tickets are issued under higher violation coverage. However, how the number of speed violations influences the number of collisions and how it relates to general deterrence is still unclear. Therefore, although the VC metric is informative it alone should not be used to determine how effective a scheduling method is.

In summary, the RSM cannot ensure the minimum travel distance, but it is good for maximizing the enforcement coverage on a variety of sites. Because the schedules are developed based on operators' decisions, this method is easy to accommodate and addresses different enforcement objectives, such as maximizing enforcement coverage area, minimizing travel distance and accounting for time halo or distance halo effects. The randomness built into this method results in higher unpredictability of the schedules, which can potentially increase the drivers' perceived risk of being detected. Given a clear quantitative objective and a set of constraints, the DSM is able to generate improved schedules. The schedules generated using this method can easily address some quantitative objectives; however, the model of the method needs to be further modified if more practical concerns are taken into account. For example, more constraints should be added if it needs to account for peak hours and distance or time halo effect. Besides, to implement the simulation, the value of the coefficient of PI in the objective function was assumed to be -1.1. The sign should be negative so that the PI value can contribute to the optimization objective, which is minimizing the sum of the combined value of distance and PI. But the influence of the coefficient's magnitude needs to be further investigated.

To better assess the RSM and DSM, other performance measures should be added such as those that address potential for collision reduction, and spatial coverage of enforcement locations. Moreover, application of the RSM was simulated in order to obtain sample test results in this thesis. In the pilot test planned for 2015 (further discussed in Section 6.4) the RSM method will be applied such that empirical results can be used to compare and assess the quality of the method.

CHAPTER 6. CONCLUSION AND RECOMMENDATIONS

This chapter summarizes the conclusions and contributions of this thesis, as well as its limitations and directions for further research. Recommendations for improving the proposed program framework, site identification process, and scheduling method are provided. The chapter wraps up with suggestions for further research.

6.1 Conclusions

The objective of this research is to develop a systematic program framework specifically for mobile photo radar enforcement (MPRE) in order to improve the site identification process and deployment strategy. The program framework integrates site identification, enforcement scheduling and deployment, and program evaluations.

A program framework entirely based on historical data from the CoE's existing MPRE program was developed. The deployment strategy was then designed using the data analysis results. The program information was provided by the Office of Traffic Safety (OTS), the department that is currently managing the MPRE program of the CoE. The data were collected from different databases of the CoE. To make the data applicable for data analysis, a multi-step data processing procedure was conducted to convert the data to a consistent format. The data from April 2009 to March 2013 included collision, speed, and violation data as well as MPRE deployment information. The proposed program framework consists of three main components: high risk location identification, enforcement activity scheduling, and program performance evaluation. The program framework imbeds the three components into a closed-loop control system, so that the three components are mutually related and interact.

A quantitative approach was proposed to screen candidate enforcement sites. Sites were evaluated by a multi-variable weighting system, which assigns a priority index to each site. The priority index accounts for site-specific attributes, including collisions by severity, speed violations, and road type of the site, which indirectly reflects the length and width of the road segment. A priority-based site selection process was proposed for monthly site selection. Besides priority index values of sites, the development of the monthly schedule should also be in accordance with enforcement capability and resource availability. The number of sites included in a monthly schedule should be somewhat larger than the estimated resulting number of sites, such that there are a sufficient number of candidate sites should there be an increase in resources. To be able to adapt to changing resource availability in a timely manner, the deployment schedules are established on a weekly basis.

A randomized scheduling method (RSM) was proposed for the MPRE program, which is realized by establishing weekly schedules based on employment operators' decisions on what time of day to visit and how long to stay at sites. The RSM accommodates the current culture and enforcement habits of the MPRE program in the CoE. However, the program culture may change with the implementation of the program framework and deployment strategy, so that a new scheduling method may be needed. A deterministic scheduling method (DSM) was developed to serve as alternative method for MPRE scheduling and also used as benchmarks for assessing the RSM. To monitor the performance of deployment strategy and make necessary adjustments, the thesis developed guidelines for short- and long-term program evaluation. The evaluation results will provide guidance and instructions on revising the proposed framework and deployment strategy. A numerical example was provided to demonstrate and test the DSM and the RSM. The performances of each method were evaluated in three aspects. The DSM demonstrated better performances in minimizing the total travel distance and emphasizing the high priority sites, but the deployments are focused on a small amount of sites with comparatively high PI values in the first half of a month; while the RSM performs better in maximizing the enforcement coverage and evenly distributing forces within a certain time scope as well as capture more speed violations.

6.2 Contributions

This research proposed the program framework, and a deployment strategy was designed for the City of Edmonton (CoE) to improve the efficiency and efficacy of its mobile photo radar enforcement (MPRE) program. However, the systematic procedure specifically for initializing or improving the MPRE program can be applied to other jurisdictions with necessary modifications that meet their local institutional structure and enforcement needs. The achievements of the research also help to fill the research gap in the methodology of a systematic program framework design specifically for MPRE.

6.3 Research Limitations

Two limitations were identified. Firstly, violation cost information for Edmonton was not available. This information is critical in weighting the relative impact of collisions and speed violations for PI computation. Secondly, although assumptions about the time halo and distance halo were used in the numerical example illustrated in Chapter 5, distance and time halo effects were not specifically considered in the proposed scheduling method because no local (the CoE, or even Alberta) studies have been performed to investigate the time halo and distance halo of MPRE.

6.4 Future Work and Recommendations

The scheduling and deployment of MPRE is a meaningful research topic that deserves much attention in research. The research results can be directly applied in a practical manner and used to provide the benefit of enhanced traffic safety. The thesis presents a framework for the operation of the MPRE program and the deployment strategy for MPRE. There is still work to be done in future research and also areas for improvement.

The scheduling and deployment strategy should be tested in a full-scale simulation. In the thesis, the test was based on a small sample of sites. In addition, special consideration (SC) sites were not considered in the simulation of RSM and DSM. How many uncertainties will be caused by SC sites in making schedules, particularly for DMS, is unknown.

The Random Scheduling Method (RSM) framework and strategy is to be tested in a small-scale pilot program planned for 2015. The pilot program is expected to be conducted through each season in order to capture seasonal effects, such as the impact of weather on driving behaviours and MPRE deployments. The results of the pilot test and enforcement operators' feedback regarding application of the RSM will inform the refinement and possible redesign of the MPRE framework.

The priority index (PI) computation process can be improved. Instead of using only midblock collisions, the collisions that occurred at other parts of the road can also be considered. Many studies verified that MPRE has strong and reliable effects on midblock collisions. As for how MPRE influences intersection collisions, little information was found in the existing literatures. However, the observed distance spillover effect, a phenomenon where the effects of MPRE are not restricted to the direct vicinity of the enforcement location and they "spill over" into adjacent areas (Chen, Meckle, & Wilson, 2002), potentially indicates that MPRE is also effective in reducing intersection collisions. Therefore, once it is determined how exactly MPRE can influence intersections, collisions that have occurred at intersections can be added into the computation of PI.

An index showing the interaction between nearby sites can be introduced into the multi-variable weighting system. Because of the distance spillover effect, if a site is surrounded by many other activated enforcement sites, it will receive a significant spillover effect. In this case, less enforcement priority should be given to this site. On the contrary, if a site has no adjacent enforced sites, it should be assigned with a relatively high priority. More research is required to find out how to compute this index and deal with the correlation of other indexes.

More traffic features and roadway features can be included in PI computation. Features may include traffic volume, pedestrian volume, and placement of traffic control devices, speed limit, and roadway features that induce speeding.

The distance halo and time halo effects can be taken into account in the development of enforcement schedules. The time halo can inform the best time interval for revisiting a site, while the distance halo can provide guidance on how far the distance should be between two sites that are enforced successively. By taking advantage of the time and distance halo effects, limited enforcement resources can be used more efficiently.

Finally, a more comprehensive set of performance measures for both short- and long-term evaluation should be developed, in order to provide better assessments of the proposed program framework and scheduling strategies.

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APPENDICIES

Table 15 Information on the Sample Sites for Numerical Example

Site ID	Site Group	Road Type	*PI*		Site ID	Site Group	Road Type	*PI*
1	SS	C	4.45		41	PR	A	5.22
2	SS	A	4.26		42	PR	A	0.95
3	SS	A	4.03		43	PR	A	0.62
4	PR	A	18.55		44	PR	A	0.52
5	PR	C	9.11		45	PR	C	0.45
6	PR	L	8.90		46	PR	C	0.32
7	PR	C	8.51		47	PR	A	0.26
8	PR	C	8.17		48	PR	C	0.18
9	PR	A	7.21		49	PR	L	0.00
10	PR	A	6.57		50	PR	C	0.00
11	PR	A	5.77		51	SS	C	3.88
12	PR	A	5.61		52	SS	A	1.88
13	PR	A	5.49		53	SS	L	1.80
14	PR	C	5.25		54	SS	L	1.80
15	PR	A	5.18		55	SS	A	1.02
16	PR	A	5.02		56	SS	A	0.95
17	SS	A	3.82		57	SS	A	0.89
18	SS	L	3.60		58	SS	L	0.81
19	SS	L	3.60		59	SS	L	0.81
20	SS	A	3.22		60	SS	C	0.72
21	PR	A	4.58		61	SS	L	0.48
22	PR	C	4.24		62	SS	C	0.48
23	PR	A	4.06		63	SS	C	0.44
24	PR	C	3.82		64	SS	C	0.40
25	PR	C	3.70		65	SS	C	0.40
26	PR	A	3.65		66	SS	L	0.33
27	PR	A	3.54		67	SS	L	0.24
28	PR	A	3.23		68	SS	C	0.21
29	PR	C	3.01		69	SS	L	0.19
30	PR	A	2.96		70	SS	C	0.17
31	PR	A	2.55		71	SS	L	0.10
32	SS	L	2.80		72	SS	L	0.10
33	SS	L	2.61		73	SS	A	0.09
34	SS	A	2.56		74	SS	C	0.08
35	PR	A	2.02		75	SS	C	0.04
36	PR	C	1.95		76	SS	C	0.04
37	PR	A	1.77		77	SS	A	0.00
38	PR	A	1.30		78	SS	C	0.00

39	PR	A	1.21		79	SS	C	0.00
40	PR	C	1.08		80	SS	A	1.03

Table 16 Weekly Schedules Generated by Randomized Scheduling Method

RSM Schedule 1		AM shift Squad 1			PM shift Squad 2		
Week	**Day**	**1st Visit**	**2nd Visit**	**3rd Visit**	**1st Visit**	**2nd Visit**	**3rd Visit**
1	1	13	4	20	28	8	7
1	2	15	16	5	9	4	13
1	3	7	12	5	3	19	21
1	4	5	16	14	4	2	11
1	5	12	29	14	24	28	21
1	6	1	29	37	27	6	4
1	7	26	1	3	16	28	8
2	8	9	4	13	8	5	16
2	9	18	2	9	3	1	8
2	10	10	27	18	14	3	15
2	11	21	5	7	11	38	29
2	12	14	23	12	6	9	25
2	13	3	19	22	11	24	7
2	14	13	20	9	11	35	18

RSM Schedule 2		AM shift Squad 1			PM shift Squad 2		
Week	**Day**	**1st Visit**	**2nd Visit**	**3rd Visit**	**1st Visit**	**2nd Visit**	**3rd Visit**
1	1	13	4	20	28	8	7
1	2	15	16	5	9	4	13
1	3	7	5	12	3	19	21
1	4	16	5	14	4	2	11
1	5	12	29	14	28	24	21
1	6	1	29	37	27	4	6
1	7	1	26	3	16	28	8
2	8	9	4	13	8	5	16
2	9	18	2	9	3	8	1
2	10	10	27	18	3	14	15
2	11	21	5	7	38	11	29
2	12	23	14	12	6	25	9
2	13	3	19	22	11	24	7
2	14	20	13	9	11	35	18

RSM Schedule 3		AM shift Squad 1			PM shift Squad 2		
Week	**Day**	**1st Visit**	**2nd Visit**	**3rd Visit**	**1st Visit**	**2nd Visit**	**3rd Visit**
1	1	5	16	14	11	28	21
1	2	26	4	20	28	16	3
1	3	7	23	29	9	31	4
1	4	5	12	16	24	8	7
1	5	14	1	12	4	6	8
1	6	15	5	3	28	21	19
1	7	37	29	1	2	4	13
2	8	20	7	5	11	35	18
2	9	9	4	13	6	7	29
2	10	9	2	13	16	5	14
2	11	22	21	12	11	3	15
2	12	13	27	10	1	8	3
2	13	18	9	3	11	25	8
2	14	18	20	14	9	32	24

RSM Schedule 4		AM shift Squad 1			PM shift Squad 2		
Week	**Day**	**1st Visit**	**2nd Visit**	**3rd Visit**	**1st Visit**	**2nd Visit**	**3rd Visit**
1	1	5	16	14	9	31	4
1	2	7	23	29	4	2	11
1	3	15	5	3	4	6	8
1	4	12	29	14	8	7	28
1	5	16	5	20	3	24	28
1	6	26	1	12	28	16	19
1	7	13	4	1	21	27	13
2	8	13	27	10	8	5	16
2	9	9	18	20	6	8	25
2	10	9	2	13	11	35	18
2	11	3	19	22	11	24	7
2	12	9	18	4	11	3	15
2	13	21	5	7	9	3	32
2	14	17	12	14	1	29	14

RSM Schedule 5		AM shift Squad 1			PM shift Squad 2		
Week	**Day**	**1st Visit**	**2nd Visit**	**3rd Visit**	**1st Visit**	**2nd Visit**	**3rd Visit**
1	1	13	20	37	21	28	31
1	2	3	1	29	21	8	2
1	3	4	1	14	13	27	3
1	4	16	29	23	4	6	7
1	5	15	12	5	4	9	8
1	6	16	5	14	4	11	28
1	7	7	5	12	19	24	16
2	8	4	13	9	7	25	15
2	9	3	13	9	11	32	14
2	10	2	19	17	18	11	3
2	11	27	18	20	11	5	16
2	12	9	12	22	6	8	3
2	13	21	5	7	9	1	8
2	14	18	20	14	35	24	29

Table 17 Weekly Schedule Generated by Deterministic Scheduling Method

DSM Schedule 1	Shift ID	1st visit	2nd visit	3rd visit	Shift ID	1st visit	2nd visit	3rd visit
	1	6	4	7	15	4	6	7
	2	5	8	14	16	5	8	9
	3	4	6	7	17	4	6	7
	4	5	8	14	18	5	8	9
	5	4	6	7	19	4	6	7
	6	5	8	14	20	5	8	9
	7	4	6	7	21	4	6	7
	8	5	8	9	22	5	8	9
	9	4	6	7	23	4	6	7
	10	5	8	9	24	5	8	10
	11	4	6	7	25	4	6	7
	12	5	8	9	26	5	8	10
	13	4	6	7	27	4	6	7
	14	5	8	9	28	5	8	10
DSM Schedule 2	**Shift ID**	**1st visit**	**2nd visit**	**3rd visit**	**Shift ID**	**1st visit**	**2nd visit**	**3rd visit**
	1	7	4	6	15	4	6	7
	2	5	8	14	16	5	8	9
	3	4	6	7	17	4	6	7
	4	5	8	14	18	5	8	9
	5	4	6	7	19	4	6	7
	6	5	8	14	20	5	8	9
	7	4	6	7	21	4	6	7
	8	5	8	9	22	5	8	9
	9	4	6	7	23	4	6	7
	10	5	8	9	24	5	8	10
	11	4	6	7	25	4	6	7
	12	5	8	9	26	5	8	10
	13	4	6	7	27	4	6	7
	14	5	8	9	28	5	8	10

DSM Schedule 3	**Shift ID**	**1st visit**	**2nd visit**	**3rd visit**	**Shift ID**	**1st visit**	**2nd visit**	**3rd visit**
	1	18	4	6	15	4	6	9
	2	5	8	7	16	5	8	7
	3	4	6	14	17	4	6	9
	4	5	8	7	18	5	8	7
	5	4	6	14	19	4	6	9
	6	5	8	7	20	5	8	7
	7	4	6	14	21	4	6	9
	8	5	8	7	22	5	8	7
	9	4	6	9	23	4	6	9
	10	5	8	7	24	5	8	7
	11	4	6	9	25	4	6	10
	12	5	8	7	26	5	8	7
	13	4	6	9	27	4	6	10
	14	5	8	7	28	5	8	7
DSM Schedule 4	**Shift ID**	**1st visit**	**2nd visit**	**3rd visit**	**Shift ID**	**1st visit**	**2nd visit**	**3rd visit**
	1	26	4	6	15	4	6	9
	2	5	8	7	16	5	8	7
	3	4	6	14	17	4	6	9
	4	5	8	7	18	5	8	7
	5	4	6	14	19	4	6	9
	6	5	8	7	20	5	8	7
	7	4	6	14	21	4	6	9
	8	5	8	7	22	5	8	7
	9	4	6	9	23	4	6	9
	10	5	8	7	24	5	8	7
	11	4	6	9	25	4	6	10
	12	5	8	7	26	5	8	7
	13	4	6	9	27	4	6	10
	14	5	8	7	28	5	8	7

DSM Schedule 5	Shift ID	1st visit	2nd visit	3rd visit	Shift ID	1st visit	2nd visit	3rd visit
	1	27	4	6	15	4	6	9
	2	5	8	7	16	5	8	7
	3	4	6	14	17	4	6	9
	4	5	8	7	18	5	8	7
	5	4	6	14	19	4	6	9
	6	5	8	7	20	5	8	7
	7	4	6	14	21	4	6	9
	8	5	8	7	22	5	8	7
	9	4	6	9	23	4	6	9
	10	5	8	7	24	5	8	7
	11	4	6	9	25	4	6	10
	12	5	8	7	26	5	8	7
	13	4	6	9	27	4	6	10
	14	5	8	7	28	5	8	7