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Relationship between Road Safety and Mobile Photo Enforcement Performance Indicators: A Case Study of the City of Edmonton

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ABSTRACT

Mobile photo enforcement (MPE) programs are commonly implemented to regulate speed and improve road safety. However, most previous research focuses mainly on validating the safety effects of MPE, with very minimal discussion on the enforcement performance indicators (EPIs). Therefore, the goal of this study is to provide a better understanding of the relationship between the three selected EPIs (number of enforced sites, average check length, and number of issued tickets) and the program's safety outcomes. In total, eight years (2005-2012) of monthly citywide data were collected and used in a generalized linear Poisson model. The results show that as the number of enforced sites and issued tickets increased, the number of speed-related collisions decreased. Also, as the average check length decreased, a greater reduction of speed-related collisions was observed. These results indicate that collision reductions were associated with a MPE program that promoted: higher spatial coverage (i.e., more enforceable locations), more frequent checks (i.e., shorter average check length), and more issued tickets. The marginal effects of enforcing 100 sites and issuing 10,000 tickets per month were calculated to be 47 and 140 fewer speed-related collisions, respectively.

Key words: mobile photo enforcement, enforcement performance indicators, generalized linear Poisson model, marginal effect

1 INTRODUCTION

Speeding is a major contributing factor to road injuries and fatalities. It was reported that around one third of fatal collisions involved speeding (National Highway Traffic Safety Administration, 2007). Unfortunately, speeding is a widespread issue throughout countries. A survey conducted among 23 countries revealed that the percentage of speeding drivers is usually between 40% and 50%, and it can be as high as 80% on some motorways and urban arterial roads (Organisation for Economic Cooperation and Development, 2006).

The relationship between legislation, compliance, deterrence and, consequently, safety goes through several stages. Previous research has shown that when a new law comes into effect, there are two means by which individuals comply with the new law (European Transport Safety Council, 2011) (ESCAPE Consortium, 2003). One is through a personal decision, which is based on an individual's beliefs about acceptable social norms. For instance, some people understand the deadly consequences of speeding and realise it is not acceptable to speed and, hence, restrain from violating speed limits, this is known as intrinsic behavior. Unfortunately, not many people adopt this behaviour. The other way by which individuals comply with a new law is through enforcement, this is known as extrinsic behavior, which is mainly motivated by external factors such as sanctions and losses.

As displayed in Figure 1, the intrinsic relationship between legislation and compliance is relatively straight forward, this, however, is not the case for the extrinsic relationship. As already noted, in the extrinsic relationship, legislation must be coupled with enforcement activity in order to encourage individuals to comply with the new law. The effectiveness of the enforcement activity is a function of the enforcement strategy and tools used; these are sometimes known as supportive measures. Depending on the effectiveness of the supportive measures, the enforcement activity puts an offender under a certain level of objective risk (the actual risk of getting caught/punished) and, consequently, a subjective risk (implied risk of getting caught). These risks combined have impacts on deterrence levels (both general and specific), causing individuals to comply with the new legislation and resulting in potential safety benefits (Wegman & Goldenbeld, 2006) (Aarts, Goldenbeld, & Schangen, 2004).

As already mentioned, the supportive measures discussed in the previous paragraph and represented in Figure 1 include factors such as enforcement strategy (spatial vs temporal coverage), enforcement instruments and tools (conventional vs automated). These measures are extremely critical to the success of any a photo enforcement program. Therefore, optimising the use of these measures by identifying the most effective strategies and tools is of utmost importance from a planning perspective. In fact, these measures have actually been used as indicators of the effectiveness of an enforcement program (i.e. Enforcement Performance Indicators) (Spooner, McPherson, & Hall, 2004; Wundersitz & McLean, 2004).

Over the years, many forms of photo enforcement have been used with the aims of achieving higher compliance rates. In conventional (manned) enforcement, police officers use speed measurement devices, such as laser guns, to check vehicle speed. The operation involves immediate and direct interaction between the enforcement officer and violator, which enables the verification of violators to be more objective (National Highway Traffic Safety Administration, 2008; Tay, 2009). However, conventional enforcement may result in traffic congestion and may pose a risk to personnel where roadside stopping is dangerous (National Cooperative Highway Research Program, 2012). Most importantly, it is difficult for the police to monitor and record speeding vehicles at high traffic volume sites. Therefore, automated enforcement was proposed as a safer and more efficient alternative to conventional enforcement, and has been introduced in many countries since the late 1980s (Organisation for Economic Cooperation and Development, 2006). The speed camera, also known as photo radar, is the most widely used form of automated enforcement in the world (National Cooperative Highway Research Program, 2012).

Speed cameras can be either fixed at certain sites or mobile by mounting them on enforcement vehicles. Fixed cameras, with the ability to also capture red-light running when installed at intersections, were found to be very effective in reducing violations and collisions at black spot areas (Gains, Humble, Heydecker, & Robertson, 2003; Tay & de Barros, 2009; Tay & de Barros, 2011; Vanlaar, Robertson, & Marcoux, 2014). However, Cameron and Delaney suggested that mobile photo enforcement (MPE) had more general safety effects on casualty collisions in an urban environment (Cameron & Delaney, 2006). This is because the existence of fixed cameras at specific sites is likely to become public knowledge, especially when the program continues for a long time period (National Cooperative Highway Research Program, 2012). Drivers were observed to slow down near enforcement devices and then speed up after passing them, which is called the “kangaroo effect” (Elvik, 1997). Mobile enforcement devices can be installed in unmarked vehicles and deployed at various sites and time periods, thereby increasing the unpredictability of enforcement and the likelihood of creating a wider range of deterrence effects (Carnis & Blais, 2013).

Many studies have validated the effectiveness of MPE on both speed compliance and safety. Most of them adopted an interrupted time series analysis or before-and-after analysis with a comparison group (Cameron, Cavallo, & Gilbert, 1992; Carnis, 2011; Chen, Wilson, Meckle, &

Cooper, 2000; Christie, Lyons, Dunstan, & Jones, 2003; Newstead, Cameron, & Leggett, 2001). The results revealed around 20% reduction in collisions, and greater reductions were observed for fatal and severe injury collisions than for property-damage-only collisions (Carnis & Blais, 2013; Newstead et al., 2001). Constantly assessing and monitoring the important metrics that characterize an enforcement program has been recognized as a fundamental component from a management perspective (Roberts, 2006). This has led many researchers into assessing the effects of enforcement performance indicators (EPIs) on road safety (Spooner, McPherson, & Hall, 2004; Wundersitz & McLean, 2004).

The Police Enforcement Policy and Programmes on European Roads (PEPPER) selected 16 main types of EPIs, including legislation, a national enforcement plan, planned enforcement, actual enforcement, violations, and sanctions (Orozova-Bekkevold et al., 2007). However, a gap exists in the literature regarding the relationship between the EPIs and safety outcomes in the field of automated mobile photo enforcement. This knowledge is highly valuable for agencies that are planning or operating MPE programs aimed to produce substantial safety benefits.

In this study, the effects of the three EPIs on changes in collisions are measured. As already noted, EPIs are a form of supportive measures. These measures impact the effectiveness of the enforcement program by increasing objective and subjective risks; these risks then affect deterrence levels, which help improve compliance and reduce collisions. All these effects (EPIs on risks, risks on deterrence, deterrence on compliance, and compliance on collisions) are confounded within the relationship between the EPIs and collisions, which is examined in this paper.

To reflect the effectiveness of the MPE program three indicators were chosen: the number of enforced sites, average check length, and number of issued tickets. The number of enforced sites is a measure of the spatial coverage of the MPE program. Average check length refers to the average number of deployment hours for one check/visit at a site, which is an essential parameter for developing the deployment schedule. These two EPIs characterize the program from the planning and implementation perspective. The last indicator, the number of issued tickets, represents the severity of the program in terms of the extent of the sanctions, it can also been seen as an indirect measure of specific deterrence (Tay, 2004; Tay, 2005a; Tay, 2009). A more detailed discussion about these EPIs is provided in the methodology section. The objective of this study is to investigate the relationship between these EPIs and the safety outcomes of the MPE program.

2 LITERATURE REVIEW

Carnis and Blais conducted an assessment of a national speed camera enforcement program in France, which commenced in 2003 (2013). By 2010, a total of 2,756 speed cameras (933 mobile ones) had been operated on the public roads and highway network across the whole country. The French authorities intentionally spread enforcement devices throughout the national road network, making it very difficult for drivers to avoid enforcement (Carnis, 2011). The study adopted interrupted time-series analyses using autoregressive, integrated, moving average (ARIMA) intervention models, which are considered suitable for examining the effects of an intervention on a time series of collision data. The results showed significant reductions in both traffic fatalities and non-fatal injuries after the introduction of the program. A 21% reduction in the fatality rate per 100,000 vehicles was found by comparing linear models with and without the enforcement variables. The stable fatal collision decrease was attributed to the high detection capacity of the enforcement devices. However, the reduction in non-fatal injuries dropped from 26.2% in 2003 to only 0.8% in 2010 after the implementation of the program (Carnis & Blais, 2013).

Queensland, Australia, applied a randomized scheduling method in its mobile enforcement program, known as Random Road Watch (RRW) (Leggett, 1997). Instead of focusing only on high-collision locations, each police station operated an individual program covering as many routes in the station’s territory as possible. This method was proposed by Edwards and Brackett (1978) to achieve a long-term, widespread collision reduction while maintaining low police presence. During the RRW, the time of day and day of the week for the enforcement schedule at each site were generated randomly, making the operation highly unpredictable. The interactive relationship between enforcement and collision reduction was continuously evaluated, which guided adjustments to the program. Newstead et al. applied a quasi-experimental study design and Poisson regression analysis to evaluate the safety effects of the program (Newstead et al., 2001). The monthly collision data were divided into four series, based on whether the collisions occurred in enforced areas and whether they occurred during the enforcement time band (i.e., daily time period during which enforcement took place). The series of collisions that occurred in the enforced areas and during the enforcement time band was compared with the other three series. Different severities of collisions were analyzed, and the largest reduction was found in fatal collisions at 31%. However, the reduction in non-fatal collisions was revealed to increase with time following the program’s implementation. The study also examined the relationship between the number of total saved collisions and the program's EPIs (coverage, offences detected, and hours enforced) in each police region, using a multivariate regression analysis. Although all three EPIs had positive estimates, only coverage, measured by the percentage of collisions that occurred in the enforced areas and during the enforcement time band, was found to be statistically significant. Finally, the benefit-cost ratio for the program was estimated to be 55:1.

Chen et al. investigated the safety effects of a covert mobile photo radar program (PRP) in British Columbia, Canada (2000). The PRP was initiated in March 1996 with a province-wide deployment of 30 covert mobile speed cameras and a public media campaign. Warning letters were first mailed to the owners of speeding vehicles and then replaced by violation tickets starting in August 1996. Naïve before-and-after analysis revealed a 50% reduction in the percentage of speeding vehicles and a 75% reduction in the percentage of seriously speeding vehicles (16 km/h or more over the speed limit) at the enforced sites. A pooled cross-sectional time-series analysis of 19 monitoring sites across the province found a 2.4 km/h reduction in vehicles' mean speed. The monthly numbers of collisions, injuries, and fatalities were analyzed with the interrupted time-series method. Motor gasoline sale was incorporated in the models as a surrogate of vehicle kilometres travelled. The results showed 25%, 11%, and 17% reductions in the numbers of daytime speed-related collisions, daytime traffic collision victims carried by ambulances, and daytime traffic collision fatalities, respectively. The reason for using only the daytime collision data was to avoid the potential effects of impaired driving road checks conducted at night during the same period. However, the evaluation used only the first year of data after the implementation, and there is a possibility that the effects may have diminished as time went on.

All the studies mentioned above have confirmed the safety effects of mobile photo enforcement using state-of-the-art methodologies. The collision reductions ranged from 11% to 31%, with higher percentage reductions in fatal and injury collisions. However, few of the previous studies explicitly discussed the impact of EPIs on traffic safety from a planning perspective. In other words, it is still unclear how to maximize the use of a program's enforcement resources to achieve citywide safety. This study was conducted to answer this question.

3 METHODOLOGY

3.1 Enforcement Performance Indicators (EPIs)

The goal of implementing MPE is to improve road safety by reducing speeding. The effectiveness of MPE (or any other law enforcement) usually depends on a number of variables, these variables are often termed enforcement performance indicators (EPIs) since they can also be used to measure the effectiveness of the enforcement program (Orozova-Bekkevold et al., 2007). Despite their importance to the success of an enforcement program, not much has been done to understand the effects of EPIs on the safety benefits of MPE programs. In this study, the effects of three EPIs on the safety outcomes of a MPE program are analysed: the number of enforced sites, average check length, and number of issued tickets.

The geographic distribution of enforcement resources represents the spatial coverage of a program. Due to the flexible deployment of MPE, the coverage of a program can vary considerably depending on how many sites are enforced. Spreading enforcement resources over a large number of sites will generate high spatial coverage, while focusing only on high-priority sites will result in low spatial coverage. The number of enforced sites should be considered carefully when comparing different MPE programs because it cannot account for the change in geographic size of different jurisdictions. For example, 100 sites may indicate high spatial coverage in a small town but may indicate low spatial coverage in a metropolitan city. Nevertheless, since there is only one jurisdiction (i.e., the city of Edmonton) considered in this study, the number of enforced sites can be used as a measure for spatial coverage in order to investigate its impact on safety. The successes of France's and Queensland's speed enforcement programs have implied the effectiveness of high spatial coverage (Carnis, 2011; Newstead et al., 2001). During France's program, the 2,756 speed cameras (both fixed and mobile) operating throughout the country's public roads and highway network made it difficult for speeding drivers to escape sanction. As for Queensland's program, the priority was to enforce as many routes as possible instead of only focusing on black spots. The study conducted by Newstead et al. revealed that the average percentage of collisions that occurred on enforced routes and during the enforcement time band exceeded 50% in different police regions (2001). Compared to limiting enforcement resources to only a small number of sites, higher program spatial coverage is more likely to generate wider public awareness of the enforcement. However, it should be noted that a higher number of enforced sites will likely lead to reduced deployment hours per site on average.

The total enforcement resources, measured in deployment hours, can be estimated based on the number of devices and the enforcement time band. For example, if all the devices are operated from 6 AM to midnight, the total deployment hours of a MPE program with 10 devices should be around 100 to 150 hours per day, accounting for lost time due to travelling between checks. The total enforcement hours will be distributed among the selected enforcement sites, according to the urgency of their safety/speeding problems. It is sometimes necessary to split the total number of hours assigned to one site into several checks, rather than deploy all the hours at once if the site is assigned a relatively large number of deployment hours. Then the average check length needs to be determined before making the deployment schedule. Unlike handheld device enforcement, which often has an average check length of less than one hour, the automatic mechanism of MPE is able to significantly extend the check length (Delaney, Diamantopoulou, & Cameron, 2003). According to limited details in the literature, the average check length ranged from one to six hours (Agustsson, 2001; Goldenbeld & Schagen, 2005; Leggett, 1988; Newstead et al., 2001; Newstead & Cameron, 2003; Walsh & Wessling, 1999). However, no justifications were provided for choosing a particular average check length. It is possible that check lengths were selected arbitrarily or simply based on previous practices. Shorter average check length allows for more checks in total, while longer average check length will reduce the time lost between individual checks but result in fewer checks being conducted overall. Since the average check length will greatly influence the deployment schedule, it is important to investigate whether it impacts the safety outcomes or not.

The abovementioned two EPIs describe the program from a planning perspective. The number of issued tickets, being the output of enforcement, represents the program's severity. It should be noted that the number of issued tickets is less than the number of violations actually captured during enforcement due to some validation issues, such as problems with the clarity of the vehicle licence plate or images with multiple vehicles, etc. Nevertheless, the number of issued tickets represents the population of drivers who were penalized. Due to the fact that drivers usually receive the ticket one or two weeks post-violation, it is reasonable to examine the impact of the number of issued tickets on a monthly basis. Monetary punishment is expected to deter violators, at least temporarily, from speeding again. Therefore, given the strong correlation between speeding and collisions (Cooper, 1997; Nilsson, 2004; Kloeden, McLean, & Glonek, 2002), a large number of issued tickets is expected to have a positive impact on collision reduction, which has been found in previous studies (Tay, 2010; 2009).

The procedure for making the deployment schedule of a MPE program is illustrated in Figure 2. First, the authority needs to estimate the total enforcement resources (i.e., deployment hours) based on the number of devices, enforcement time band, and other considerations. The second step is to determine the number of enforcement sites and where they are distributed geographically. The selected sites should be prioritized according to their collision/speed profiles. The third step is to calculate the number of checks for each site based on the average check length. The last step is to design the optimized daily deployment route for each enforcement device. In summary, although the quality of the site selection, as well as the determined average check length, will influence the number of issued tickets, the three EPIs are relatively independent in measuring different aspects of a MPE program.

3.2 Generalized Linear Model (GLM)

In this study, a generalized linear model (GLM) was adopted to examine the relationships between the number of collisions and a large number of explanatory variables. Compared with the traditional linear regression model, the parameters of the GLM are not estimated using the ordinary least squares method but instead the maximum likelihood method, which allows for various dependent variable distributions. The most commonly used distributions for collision modelling are the Poisson distribution and the negative binomial distribution (Chen & Tarko, 2013; El-Basyouny & Sayed, 2013). In this study, the Poisson distribution was adopted because the citywide collision data was not found to be over-dispersed $(\varphi = 0.01)$.

In the model, the number of monthly citywide speed-related collisions (i.e., collisions where speed was indicated as a contributing factor in the collision report) is the dependent variable, while the enforcement variables, employment rate, and other factors were the explanatory, or independent, variables. While more effective speed enforcement through the EPIs may also significantly influence other types of collisions, analysing their effects on speed-related collisions only helps avoid overestimating their effects.

Since the number of monthly citywide collisions is the dependent variable, it is important to account for the variation of traffic exposure. The dominant measure of traffic exposure is vehicle kilometres travelled (VKT) (El-Basyouny, Barua, & Islam, 2014; Haynes et al., 2008). The VKT of one road segment is the product of its length (in kilometres) and its traffic count (e.g., annual average daily traffic). Thus, the citywide VKT is the sum of the VKTs of all the road segments within the city, which requires permanent traffic count stations on each segment throughout the entire city. Unfortunately, such devices do not exist. Alternatively, employment rate and leading index were proposed as proxies for traffic exposure (Tay, 2003). In this study, employment rate is used, and a previous study indicates that an increase in employment rate is associated with an increase in traffic count (Tay, 2010).

It should be noted that since the number of enforced sites, average check length, and the number of tickets were generated from the same event, it is not possible for them to be entirely independent of each other. However, the correlation coefficients among these three variables were low, indicating it is acceptable to incorporate all of them in the model. Moreover, attempts were made to include interaction variables in the model, but these variables turned out to be statistically insignificant.

In addition to the EPIs the model also included, 11 monthly dummies (December was set as the baseline), a trend variable, and a police reporting threshold dummy variable. These variables were included in the model to account for the impacts of seasonality, general road safety trends, and the rise of the police reporting threshold of property-damage-only (PDO) collisions in 2011 respectively. The model form is shown in Equation 1. The dependent variable (the number of monthly citywide speed-related collisions) is linked to the explanatory variables through a log function. The parameters were estimated in SAS using the GENMOD procedure (SAS Institute Inc., 2012), which conducts the maximum likelihood estimation with the Newton-Raphson algorithm.

$$\ln(\mu) = \beta_0 + \beta_{1-11}\text{ Monthly Dummies} + \beta_{12}\text{ Employment Rate} + \beta_{13}\text{ Trend} + \beta_{14}\text{ Threshold} + \beta_{15}\text{ Number of Enforced Sites} + \beta_{16}\text{ Average Check Length} + \beta_{17}\text{ Number of Issued Tickets} \quad (1)$$

Where, μ is the distribution mean of the dependent variable and $\boldsymbol{\beta}$ is a vector of parameters to be estimated. A significant parameter indicates that the variable does have an influence on the dependent variable, while the sign of the parameter suggests whether it is a positive or negative influence.

For the variable that has significant parameters, it is meaningful to measure the corresponding change of the dependent variable given a one-unit increase of this variable, which is called the marginal effect. The marginal effect can be estimated by taking the partial differential of the equation. For the generalized linear model with the log link function shown in Equation 1, the marginal effect of the variable x_i is the product of the predicted value of the dependent variable μ and the corresponding parameter β_i of the variable, as shown in Equation 2. To obtain an overall marginal effect, μ can be substituted by the data mean of the dependent variable.

$$\frac{\partial E(\mu \mid x_i)}{\partial x_i} = \mu \cdot \beta_i \quad (2)$$

4 PROGRAM AND DATA DESCRIPTION

The City of Edmonton, Alberta, Canada uses photo radar to conduct automated mobile enforcement. The devices are installed inside enforcement vehicles, all vehicles are overt vehicles (10 marked and three unmarked), which are managed by enforcement operators. Both marked and unmarked vehicles are well known and recognizable by the public, hence, their effects on public awareness are similar. Most unmarked vehicles have the same make and model, are always parked along the road during the operation (typically in the same spot), and are left running while parked with the operator sitting in the driver’s seat. So, while they are unmarked, their make, model, and location are generally known. In fact, most mobile photo enforcement locations in the City of Edmonton are made available online for the public on the City’s website, hence, there is little doubt about the effects of increasing spatial coverage on awareness.

Enforcement sites are selected according to provincial guidelines (Alberta Justice and Solicitor General, 2014) and local expertise, covering different types of roads (arterial, collector, and local) in the city. Each site has its own start date and may be removed from the enforcement list after a period of time to better utilize the enforcement resources. The enforcement time band extends from 6 AM to 2 AM the next day and is divided into two 10-hour shifts. During each shift, the enforcement vehicles rotate among different sites, and each check at a site usually lasts between one and two hours. The total deployment hours of one site varies greatly, depending on the urgency of each site. During the enforcement operation, the speeds of passing vehicles are measured and vehicles travelling above the speed limit are photographed. The owner of the vehicle will be mailed a speeding ticket after the validation and verification of the violation.

This study used an eight-year time period (January 2005 to December 2012), which is longer than in most previous research. The citywide number of speed-related collisions and enforcement statistics were collected from separate databases of the City of Edmonton and then aggregated by month. As described in the methodology section, three EPIs were selected to examine their relationships with the program's safety outcomes. The average check length was calculated as the ratio between the monthly total deployment hours and monthly total checks. As for the monthly employment rate, the data were collected from the website of Statistics Canada.

In total, there were 96 monthly data entries. The summary statistics and the monthly values of each variable are provided in Table 1 and Figures 3 to 7, respectively. The prolonged timeline, remarkably large scale, and high-quality data of this MPE program make it an ideal case to examine the impacts of the EPIs.

Figure 3 shows the monthly variation of speed-related collisions. An obvious seasonal pattern can be observed; more collisions occurred during the winter months, with peak values usually in December. This is mainly due to unfavourable road conditions caused by snow and ice, especially in cities at higher latitudes. There was also a slight increasing trend in collisions during the first several years of the study period. A noticeable drop was seen in 2011 due to an increase of the police reporting threshold. The threshold was raised from $1,000 to $2,000 for property-damage-only collisions, effective in January 2011. Therefore, the analysis should account for the effect of this threshold change on the number of recorded speed-related collisions.

Figure 4 shows the variation of the employment rate during the study period. It seemed to fluctuate with a cycle of approximately four years. Some studies revealed a positive relationship between employment rate and the number of traffic collisions, demonstrating that a higher employment rate is associated with more collisions (Beeck, Mackenbach, Looman, & Kunst, 1991; Mercer, 1987; Susan, 1984).

As shown in figure 5, the monthly number of enforced sites remained relatively stable between 70 and 150 from 2005 to 2009. However, there was a remarkable increase during 2010 and 2011, followed by a sudden drop in 2012. The highest number of enforced sites was 402 in March 2012, and the lowest was 72 in February 2005.

Figure 6 shows the monthly variation of the average check length. The general trend of the monthly average check length was similar to that of the monthly number of enforced sites, except that there was no drop at the end of the study period. The value increased from around one hour to more than two hours from 2010 to 2012.

Figure 7 shows the monthly variation of the number of issued speeding tickets. More tickets were issued during the summer months than the winter months, with the highest value being as much as eight times the lowest value. This pattern is again mainly caused by the seasonal changes in road conditions. Road conditions are much better in summer months, which entices drivers to drive more aggressively. In general, there was no clear increasing or decreasing trend throughout the study period, with respect to the monthly number of issued tickets.

5 RESULTS AND DISCUSSION

In total, 96 monthly observations were used in the model estimation. The Chi-square statistic against the constant model (i.e., not containing any variables) was highly significant ($p<0.001$) and the McFadden's Pseudo R-squared was 0.66, which indicate that the model provides a fairly good fit to the data.

The estimated parameters are shown in Table 2 and all of them are significant at the 0.01 level. All the monthly dummy parameters have a negative sign, indicating that, on average, more collisions occurred in December than in any other month of the year. The employment rate was shown to be positively related to the number of speed-related collisions, which is consistent with previous studies (Beeck et al., 1991; Mercer, 1987; Susan, 1984). A higher employment rate is believed to be linked to more traffic on roads, and consequently, more collisions. A slight increasing trend was observed in the model. The increase in the police reporting threshold of PDO collisions resulted in a significant reduction in the number of recorded speed-related collisions, as can be seen in Figure 3.

All three EPIs, including the number of enforced sites, average check length, and number of issued tickets, were statistically significant. Therefore, the MPE program reduced the number of speed-related collisions, which realizes the goal of the Automated Traffic Enforcement Technology Guidelines in Alberta (Alberta Justice and Solicitor General, 2014).

The number of enforced sites, which is a measure of the program spatial coverage, was found to have a negative relationship with collision frequency, meaning that a higher number of enforced sites, while keeping all else constant, is associated with fewer speed-related collisions. A possible explanation is that the spatial coverage of a program reflects its exposure to the public at the spatial level. Most commuters spend the majority of their driving time on very limited routes to and from home, the workplace, and markets. Higher spatial coverage will enable the program to affect or be witnessed by a larger population of drivers. Increased public awareness of the MPE program will eventually translate to fewer collisions. In contrast, if all the enforcement resources were assigned to only a small number of sites, the safety benefits could be limited to the adjacent areas of the enforcement sites, rather than spreading throughout the city. The result of this study is consistent with the principles applied to both the RRW in Queensland and the speed enforcement program in France.

Although increasing spatial coverage could reduce the average check length at a site, this is not necessarily the case. As already defined, the average check length is the average number of deployment hours per visit to a certain site. Therfore, if a site was visited twice a day and the check length is two hours for each visit, the average check length per visit in this case would be two hours. Now if the site was only visited once a day for two hours and the other two hours were spent at another site (increased spatial coverage), the site would still have an average check length of two hours.

With that being said, the model results actually indicate that even if an increased spatial coverage were to cause a reduction the average check length, both changes would have positive effects on safety. As already stated, the model outputs indicate that increasing spatial coverage would result in a reduction in speed related collisions, moreover, the model also shows that shorter average check lengths (which may or may not be a result of increasing spatial coverage) also results in a reduction in speed related collisions.

A possible explanation for shorter average check lengths being associated with a reduction in collisions could be related to the increased flexibility it brings to the enforcement program. More specifically, a shorter average check length enables the program to be more easily tailored to the needs of each site. Due to differences in road type and roadside development, it is possible for enforcement sites to have distinguishable time patterns of traffic volume and speed violation. By using a shorter average check length, more checks at a single site or at multiple sites (increased spatial coverage) can be scheduled and more precisely implemented during times when there are more speeding problems. For example, the sum of checked vehicles during two separate one-hour checks at the morning peak hour and evening peak hour will most likely exceed that of a two-hour check in the evening only. Similarly, a shorter average check length, although not clearly reflected in the dataset, increases the potential for maintaining a larger number of enforced sites. For example, one two-hour check at one site can be split into two checks at different sites (ignoring the time loss due to travel between sites). This will prepare the program for higher potential coverage. Based on the historical data and model results, it is recommended that the average check length be kept below two hours.

The number of issued tickets, was also found to have a negative relationship with collision frequency. In other words, issuing more speeding tickets, while keeping all else constant, will result in a greater reduction of speed-related collisions. The reason here could be that violators, who are more likely to be involved in traffic collisions (Cooper, 1997), will become more cautious after being punished. It should be noted that the number of issued tickets, like the number of collisions, has a seasonal pattern due to the change in road conditions. It is not suitable to state that the program captures higher percentages of total violations in the summer months than in winter months, since more violations occurred during summer months. Nevertheless, it can be interpreted that higher percentages of drivers are affected due to the higher objective risks when the number of issued tickets is high, which leads to improved road safety. Issuing more tickets is usually associated with a higher portion of the speeding drivers who have been affected by specific deterrence. The result is consistent with Tay's (2010) study.

It is also important here to point out that, while increasing spatial coverage might mean spending less time at high-risk location, it does not always result in fewer tickets issued. The reason here is that, even at high risk locations the risks might not be as high during different parts of the day, hence, utilizing resources at other locations, with a lower overall risk but a possibly higher risk during a certain part of the day, could result in the same amount of tickets issued, if not more. For instance, some roads might have extremely high violations during peak hours, and could be considered high-risk locations. However, during other times of the day these locations might experience very low traffic volumes. In other words, keeping the number of tickets constant while increasing spatial coverage is possible if enforcement officials target high-risk hours as opposed to high-risk locations.

Additional tests were conducted specifically to examine the significance of the enforcement variables. The reduced models (i.e., models where an enforcement variable has been omitted) were each compared with the full model. The likelihood ratio Chi-square statistic, also called the G^2 statistic (Sokal & Rohlf, 1995), is calculated as twice the log-likelihood difference between the full model and the reduced model. The null hypothesis is rejected when G^2 is larger than the critical value of the Chi-square distribution with one degree of freedom. It was found that the G^2 statistic for the number of enforced sites, average check length, and number of issued tickets were 29.30, 9.31, and 128.66, respectively. Since all the G^2 values are larger than the critical value $(6.63, \alpha = 0.01)$, none of the enforcement variables should be excluded from the model. In addition, a sensitivity test was conducted (i.e., using quarterly instead of monthly values). It was found that the model has a McFadden's Pseudo R-squared of 0.79 and all the EPIs keep the same signs as the monthly model, confirming the findings. The expected monthly numbers of speed-related collisions are plotted against the observed data in Figure 8.

As mentioned in the methodology section, the marginal effect of one variable is the product of the expected number of collisions and the estimated variable parameter. Thus, the magnitude of the parameter can be seen as the reduction ratio. The mean of the observed monthly speed-related collisions is used to represent the general expected number of collisions in Equation 2, and the marginal effects of enforcing 100 sites and 10,000 issued tickets were estimated to be 47 and 140 fewer speed-related collisions per month, respectively. In addition, the benefit of changing the average check length from two hours to one hour is estimated to be 75 fewer speed-related collisions per month. The marginal effect of issuing 10,000 more tickets is comparable to that observed in (Tay, 2010). In this study, the number of reduced speed-related collisions associated with issuing that amount of tickets is estimated to be 140; in (Tay, 2010), the number of reduced injury collisions associated with issuing the same amount of tickets was estimated to be 57. The ratio between speed-related collisions and injury collisions is around 4:1 in Edmonton, which shows that there some parallelism between the results.

6 SUMMARY AND DISCUSSION

Although mobile photo enforcement (MPE) has been widely used to reduce speeds and improve road safety, a gap exists in the literature regarding the relationships between enforcement performance indicators (EPIs) and the program's safety outcomes. In this study, the number of enforced sites, average check length, and number of issued tickets were selected as three important EPIs, and their impacts on safety were investigated. The number of enforced sites measures the coverage of the program; the average check length is an important element in shaping the deployment schedule; and the number of tickets represents the severity of the program. The significance of all the EPIs validated the safety effects of the program. It was found that a higher number of enforced sites and shorter average check length are able to produce a greater reduction in collisions. At the same time, more issued tickets also have a positive impact on collision reduction. These results suggest that a successful MPE program should promote higher coverage, more frequent checks, and more frequent sanctions. The explanation for the findings can be attributed to increasing the program's public exposure as well as the certainty of detection, which was found to be the most important aspect of the deterrence effect (Homel, 1988). Finally, the marginal effects of enforcing 100 enforced sites and issuing 10,000 issued tickets per month were estimated to be 47 and 140 fewer speed-related collisions, respectively.

Although this paper provides valuable insight to the significant effects of EPIs on improving safety, the study also has a few limitations. One limitation is that this study examined the impact of the MPE program on speed-related collisions only. Tay (2010) has found that the MPE program also has a significant reduction effect on injury collisions. Therefore, it is meaningful to investigate the impacts on other types of collisions. Another concern is the transferability of the findings to other jurisdictions. Due to the differences in geographic and demographic aspects, the exact value of EPIs may only serve as a reference as mentioned in the methodology section. It is favourable to modify the EPIs with regards to the abovementioned factors. Overall, the findings of this study are limited to the data provided by the City of Edmonton. Similar studies with different datasets from other jurisdictions are needed to validate the results from this study.

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Table 1 Summary Statistics of Data

	Mean	Standard Deviation	Minimum	Maximum
Speed-Related Collisions	1479	336	949	2507
Employment Rate (%)	68.6	1.5	65.9	71.7
Number of Enforced Sites	157	82	72	402
Average Check Length (hrs)	1.40	0.41	0.90	2.38
Number of Issued Tickets	13258	5553	3481	27369

Table 2 Model Estimation Results

Number of Observations	96	
Log-Likelihood	-1310.5	
McFadden's Pseudo R-Squared	0.66	
Dependent Variable	Monthly Number of Speed-Related Collisions	
Independent Variables	Parameter Estimates	Standard Error
Intercept*	5.8888	0.1865
January*	-0.0642	0.0118
February*	-0.2238	0.0126
March*	-0.1256	0.0133
April*	-0.3646	0.0153
May*	-0.3110	0.0158
June*	-0.2732	0.0155
July*	-0.3085	0.0169
August*	-0.2577	0.0173
September*	-0.2025	0.0147
October*	-0.1791	0.0144
November*	-0.0913	0.0127
Employment Rate (%)*	0.0241	0.0026
Trend*	0.0032	0.0002
Threshold*	-0.4252	0.0175
Number of Enforced Sites (per 100 sites)*	-0.0320	0.0059
Average Check Length (hrs)*	0.0507	0.0166
Number of Issued Tickets (per 10,000 tickets)*	-0.0946	0.0083

* Significant at 0.01 level

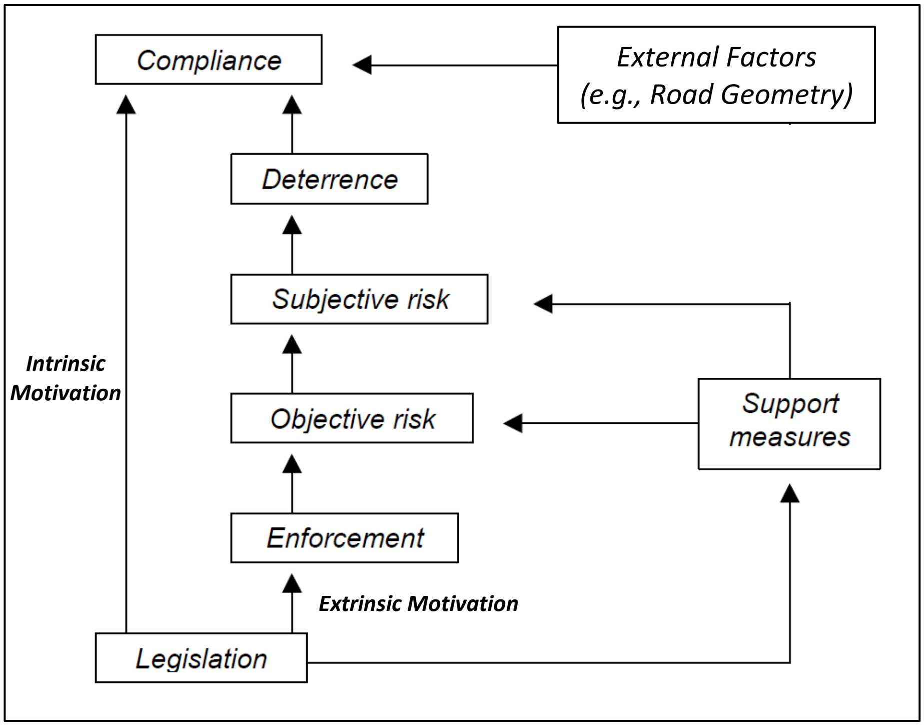

Figure 1 Mechanism of Traffic Law Enforcement

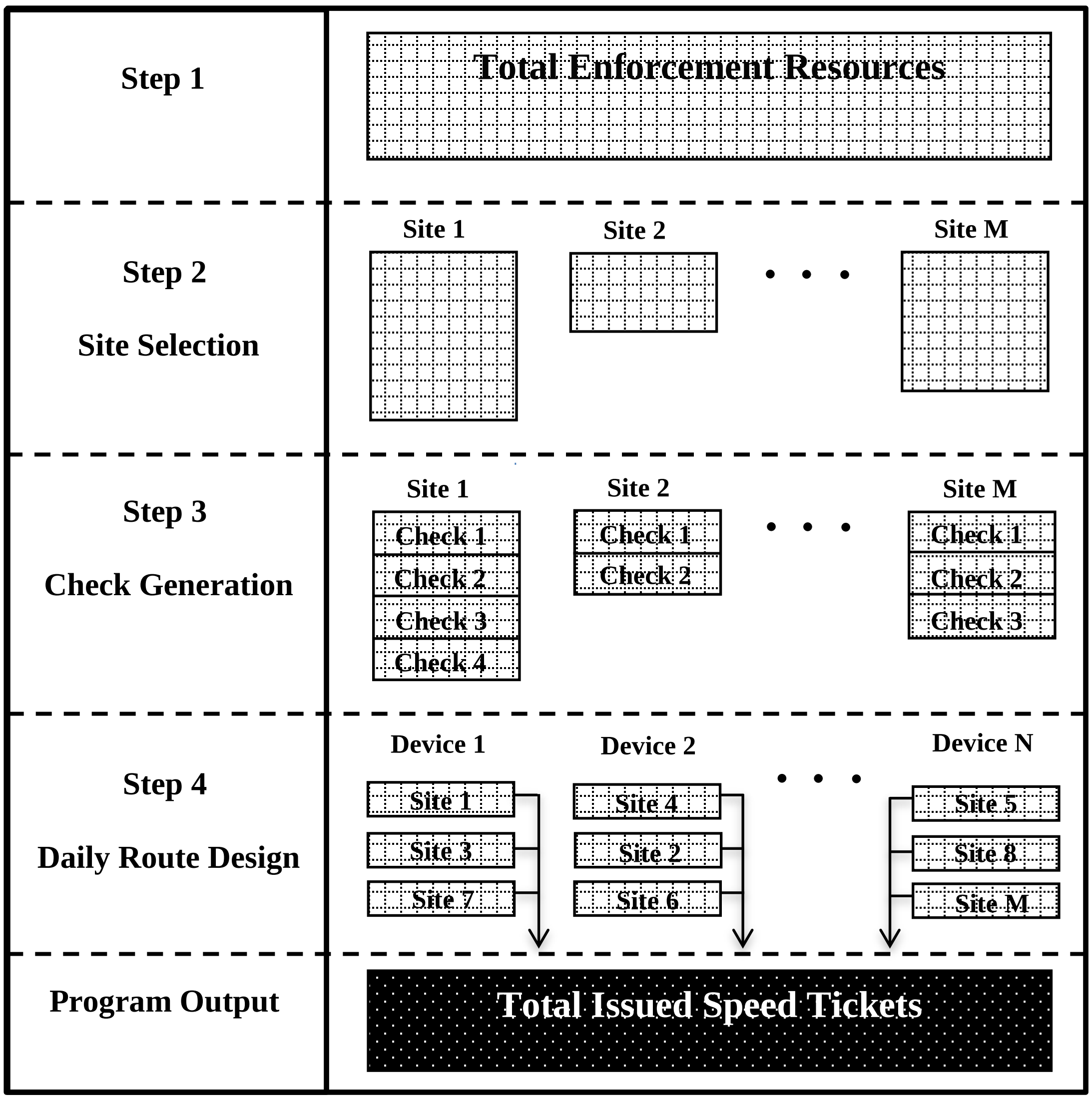

Figure 2 MPE Deployment Scheduling Procedure

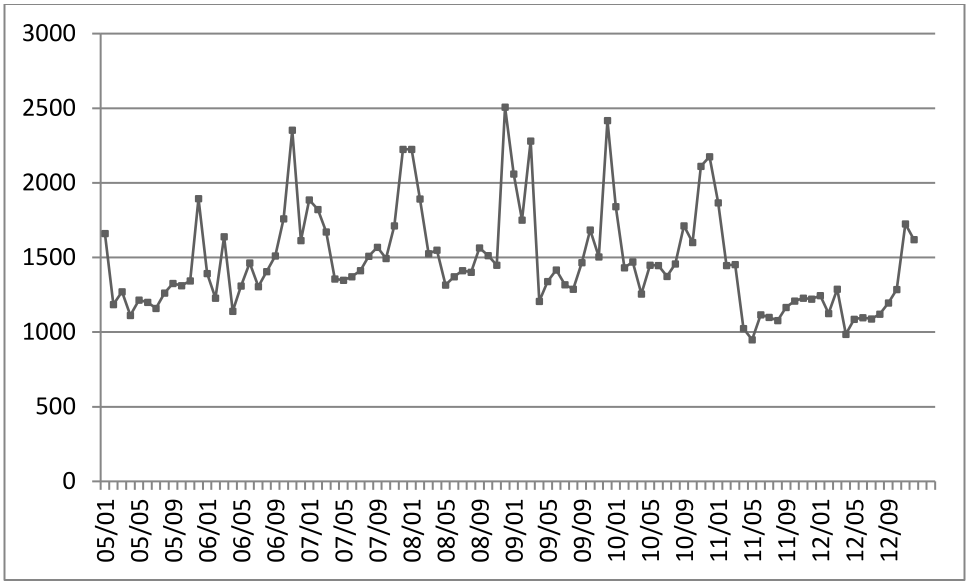

Figure 3 Monthly Number of Speed-Related Collisions

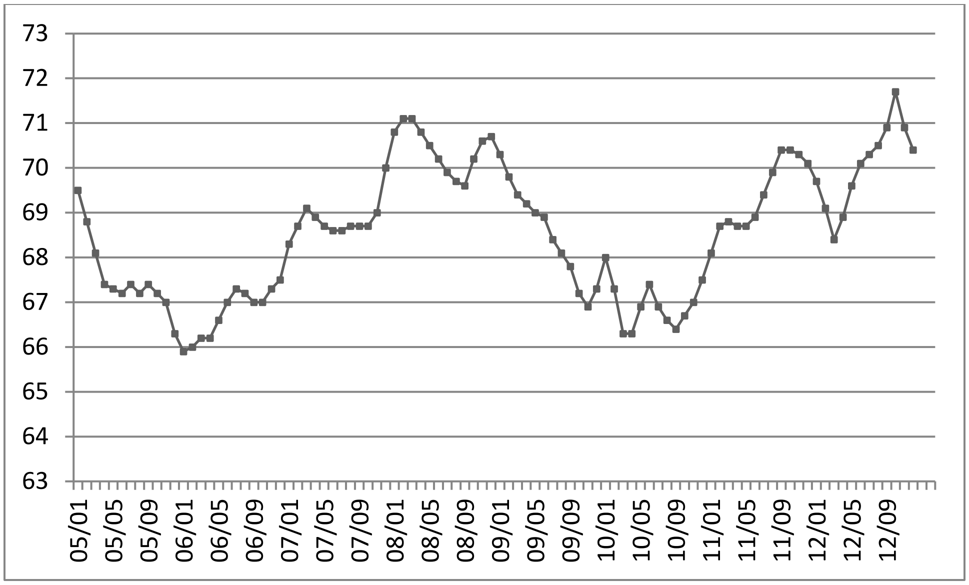

Figure 4 Monthly Employment Rates (%)

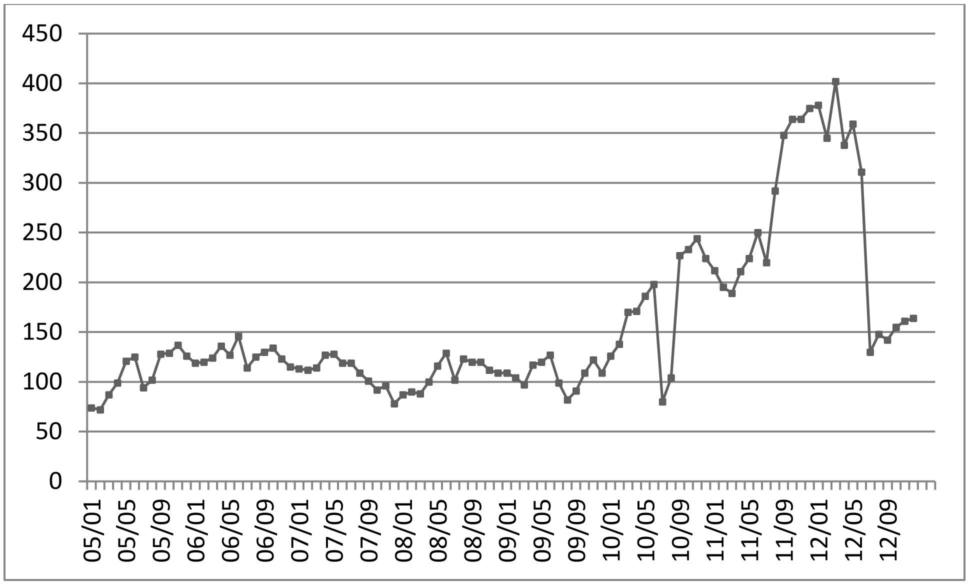

Figure 5 Monthly Number of Enforced Sites

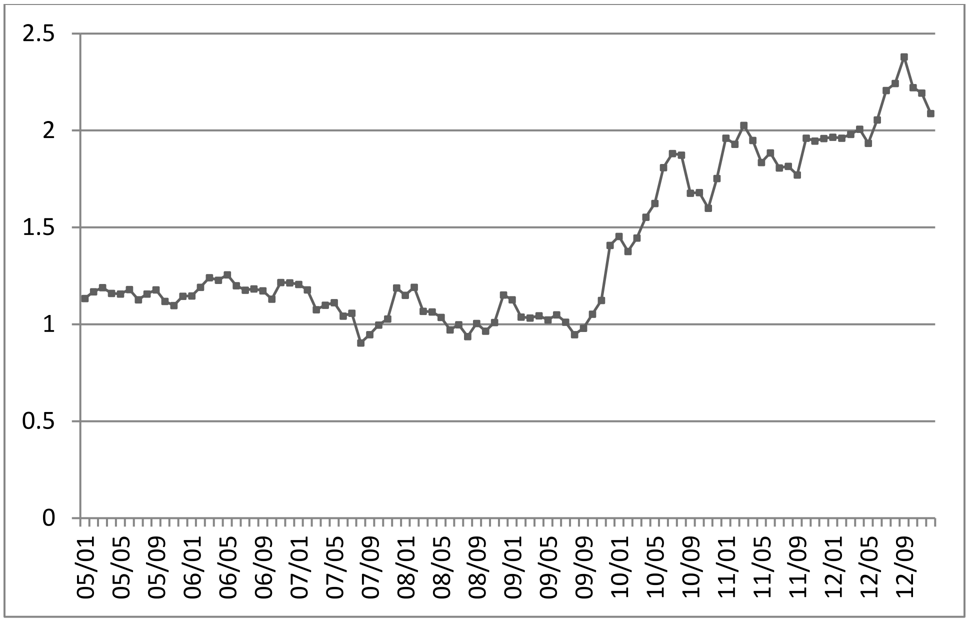

Figure 6 Monthly Average Check Length (hrs)

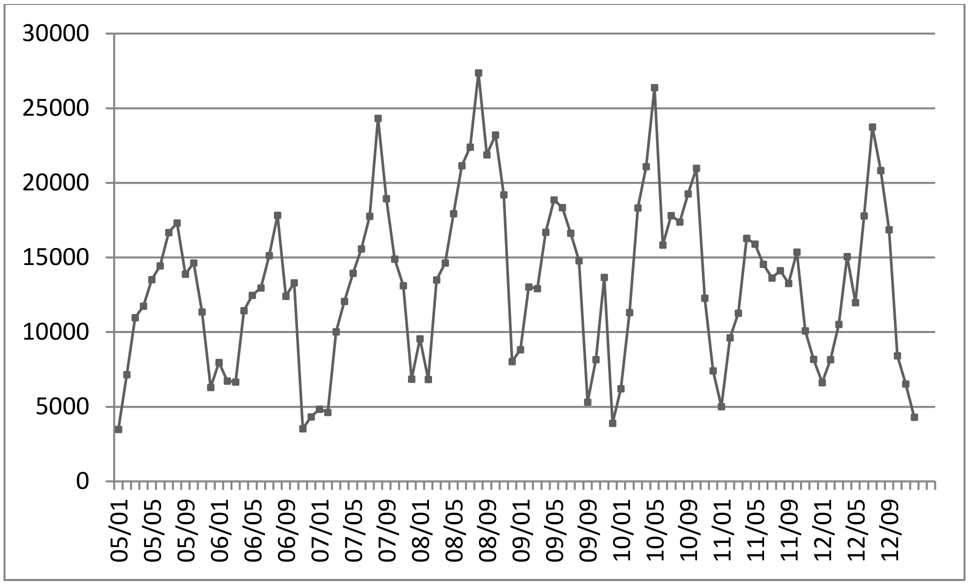

Figure 7 Monthly Number of Issued Tickets

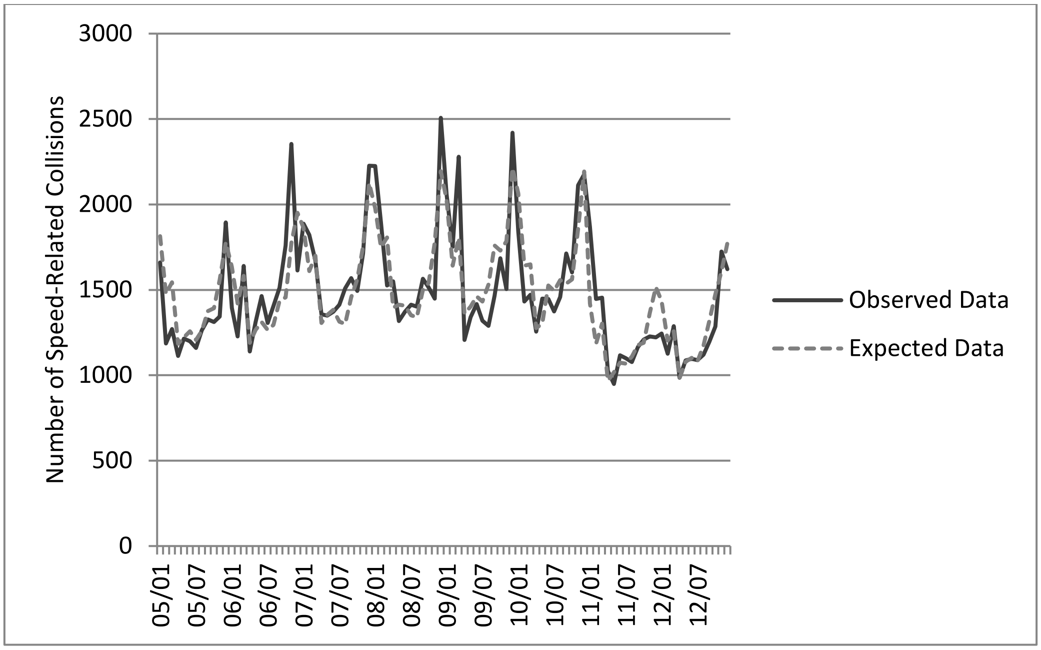

Figure 8 Expected vs. Observed Monthly Speed-Related Collisions