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EFFECTIVENESS OF INNOVATIVE SPEED-ENFORCEMENT TECHNIQUES IN ILLINOIS

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16. Abstract

The effects of various police patrolling methods on the average speed and crash rate were studied in this report. The number of speeding citations under various enforcement strategies was also investigated. Two surveys were designed and conducted for this purpose, a pilot and a statewide study. The results show that speed enforcement had a statistically significant effect on reducing the average speed, which is more evident during the morning peak period. The average-speed analysis indicates the existence of time halo, as drivers maintain lower speeds for some period after enforcement stops. The minimum length of time halo was found to be at least 2 weeks. A methodology for the optimal allocation of enforcement resources is presented, along with recommendations for strategy selection and deployment.

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EXECUTIVE SUMMARY

Speed enforcement is one of the major approaches available to traffic organizations to reduce crash rates and increase safety. The Illinois Department of Transportation (IDOT) and the Illinois State Police (ISP) have initiated a program to improve highway safety. The program includes encouraging speed-control studies, identifying crash-prone locations, and initiating innovative speed-enforcement techniques. At the core of this program is the development of a fact-based body of knowledge on the relative impact and effectiveness of various enforcement strategies, which relies on understanding and quantifying how drivers respond to various enforcement approaches. This information would form the basis for the effective deployment of enforcement resources to achieve the agency's safety objectives. The present study is intended to address the need that IDOT and the ISP have for field-validated information on speed-enforcement effectiveness. Accordingly, the main objectives of the study are the following:

- Investigate the effects of alternative police patrolling techniques and strategies on the average speed, crash rate, and number of citations
- Identify effective enforcement parameters, such as time of day (morning peak, afternoon peak, and nonpeak) and patrol duration
- Ascertain the existence of the time halo and characterize its properties, if applicable (time halo is defined as the time until the effects of enforcement on driver speed completely disappear)
- Provide recommendations on optimal allocation of enforcement resources

A comprehensive literature review and interviews with enforcement agency personnel resulted in the design of field experiments to measure and ascertain the effectiveness of various enforcement strategies. A two-stage approach to the fieldwork was followed. First, a pilot study with a limited geographic scope was performed, using two highway segments in East St. Louis. The findings of the pilot study were used to design the second, statewide study, which expanded the geographic scope of the fieldwork and hence the applicability of the results.

Beyond the qualitative insights and quantitative results obtained as a result of the fieldwork, which can be used by the enforcement agency in planning its operational deployments, the study provides a systematic procedure for incorporating the study findings to allocate enforcement resources optimally for various patrolling techniques at locations. Application of the model with selected input based on the study yields specific recommendations for patrol effectiveness.

The principal findings of this study can be summarized in the following:

- Enforcement effects were more favorable during the morning peak period in comparison with other time periods. Furthermore, the enforcement strategies had the least favorable effect during the afternoon peak period.
- The enforcement resulted in a greater reduction in the average speed during weekends than during weekdays.
- The time halo was found to be at least 2 weeks.

- The time halo can be used to reduce enforcement cost. The study findings suggest that using fewer patrol units, while taking advantage of the time halo, could produce virtually the same outcome as employing more patrol units.
- The results of the data analysis revealed that starting with high-intensity enforcement and then progressively lowering the intensity produced a more favorable outcome than starting with low intensity and progressively increasing it.
- The stationary covert strategy was the most effective method, considering the ability to cite violators and reduce the average speed.
- Stationary overt and circulating overt strategies were more effective in reducing the average speed but less effective in citing the violators.
- The sensitivity analysis based on the mathematical programming formulation revealed that it is very important to set appropriate objectives for the enforcement plan.
- It is also recommended that two patrol units be used on the segments to increase both efficiency and effectiveness of the enforcement.

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CHAPTER 1 INTRODUCTION AND BACKGROUND

Evidence clearly shows that inappropriate speed is a major factor affecting road-accident frequency and severity. According to the National Highway Traffic Safety Administration (NHTSA), speeding was the main cause of 30% of all fatal injuries in 2003 (NHTSA, 2005). Speed enforcement to control speeding is one of the major approaches available to traffic agencies to reduce crash rates and increase safety.

The Illinois Department of Transportation (IDOT) and the Illinois State Police (ISP) have initiated a program to improve highway safety. The program includes encouraging speed-control studies, identifying crash-prone locations, and initiating innovative speed-enforcement techniques (e.g., Motorcycle Enforcement Bureau). At the core of this program is the development of a fact-based body of knowledge on the relative impact and effectiveness of various enforcement strategies, which relies on understanding and quantifying how drivers respond to various enforcement approaches. This information would then form the basis for effective deployment of enforcement resources to achieve the safety objectives of the Illinois Department of Transportation (IDOT).

The present study is intended to address the need that IDOT and the ISP have for field-validated information on speed-enforcement effectiveness. Accordingly, the main objectives of the study are as follow:

- Investigating the effects of various police-patrolling methods on the average speed, crash rate, and number of citation
- Identifying effective enforcement time (morning peak, afternoon peak, and nonpeak) and duration
- Documenting the existence of the time halo and characterizing its properties
- Providing recommendations on optimal allocation of enforcement resources

Before describing the tasks undertaken to accomplish the above objectives and the study methodology, the general background and findings from previous studies on the effectiveness of enforcement strategies are presented.

Although the first automated speed-enforcement program was applied in the United States in 1910, automated speed enforcement was not used by law enforcement agencies until 1987, when photo-radar enforcement was first applied in Paradise Alley, Arizona. Using automated speed enforcement is still not common, and only 11 states and the District of Columbia use this kind of enforcement (Rodier et al. 2007). Most states currently use conventional speed-enforcement methods, and police patrolling units are directly responsible for speed enforcement.

The literature in the field of speed enforcement and highway safety can be categorized into three groups based on the objective of the study and its methodology. The first group consists of studies that analyze only historical crash data to investigate the effects of enforcement on the crash-rate changes. The second group consists of studies that seek to assess and improve the performance of existing speed-enforcement programs. Studies in the third group focus on designing new enforcement programs.

In the following sections, a review of previous studies in each of the three categories is presented.

1.1 ANALYZING AVAILABLE DATA

Several studies in the literature focused on available historical data under the existing enforcement programs. These studies were based primarily on time series data and generally tried to determine the effects of enforcement over some period in the past, by analyzing the changes in accidents rates. Hess (2004) analyzed the effects of enforcement cameras on the number of injury accidents. Time-dependent effects (e.g., seasonal effects) were the major challenge in his study. These effects could reduce the accuracy of the comparison between various time intervals. The data for this study were obtained from the database of injury crashes recorded in Cambridgeshire, United Kingdom, between 1990 and 2002. The results showed a reduction of 45.74% in the crash numbers near the camera sites, while less reduction was observed in the wider surrounding areas. He also analyzed the effects of this type of enforcement on various road types. Not surprisingly, the results showed that the highest reduction in crash rate occurred on roads with high rates of speeding violations.

Mountain et al. (2005) also tried to predict the impact of speed-management decisions on accident rates. The data for that study were gathered from 149 speed-management schemes on 30-mph roads throughout Great Britain. These sites included 79 speed-enforcement cameras and 70 engineering schemes of different types. The crash data covered 3 years prior to and 3 years after implementation of each speed-control decision. They used the results from the various places with the same speed-management schemes to estimate the parameters of their model. Their results showed that speed-management schemes are more effective on roads with higher average speed, and vertical schemes are the most effective method in reducing the mean speed and the accident rate.

Yannis et al. (2007) conducted a study in Greece to analyze the effects of increasing police enforcement on crashes at the national and regional levels. They used aggregated data from 49 counties in Greece (245 observations in total) in the period between 1998 and 2002. In their analysis, they focused on drinking-and-driving violations by considering the number of crashes, the number of alcohol-control pull overs, and the number of speed violations. Their results showed that increasing police enforcement had positive impacts on reducing the crash rate. They also found that the enforcement strategies were more effective when designed for a specific group of people.

Another time series study was conducted by Welki and Zlatoper (2009), using aggregated annual crash data to estimate several regression models for six different types of motor vehicle fatalities: car occupants, light-truck occupants, large-truck occupants, motorcyclists, pedestrians, and pedal cyclists. By using vehicle miles traveled (as an indicator of the changes in travel behavior), they showed that some enforcement policies, such as arresting drunk drivers, could have life-saving effects; but not all groups are beneficiaries.

1.2 EVALUATING EXISTING ENFORCEMENT PROGRAMS

Studies in the second group mostly focus on evaluating the effectiveness of the current enforcement systems, as they seek more efficient use of the available infrastructure and resources.

Some of the studies have focused on police patrol strategies and their impact. These enforcement strategies are widely used in practice as the traditional and primary method of speed enforcement. Sisiopiku and Patel (1999) studied the effects of police patrol presence along the I-96 Interstate Highway in Ionia County, Michigan. The patrol was provided by the Ionia County Police Department, and two police patrols were circulating in both west- and eastbound directions during the study period (6 days). The study area had two lanes in each direction, and the speed limit had been increased recently from 65 to 70 mph for passenger cars. Aggregated speed data were collected by means of seven vehicle magnetic imaging (VMI) traffic counters. The researchers used average speed to analyze the effects of police enforcement in the study area. They evaluated the effects of police presence by comparing speeds at the police vehicle location with speeds at downstream sections. Their results showed a significant reduction in the average speed upstream of the police patrol. However, vehicles increased their speed as they passed the police vehicle. Thus, no halo effect (time or distance halo) was reported in the study.

The effects of police patrols have been widely studied in work zones. Richards et al. (1985) investigated the immediate effects of police enforcement in work zones. Several strategies were used: stationary patrol car, circulating police car, stationary patrol car with lights on, stationary patrol car with radar on, and police traffic controller. Speed reductions of 3 to 19 km/hr (approximately 2 to 12 mph) for various strategies were observed. Their study showed that the effect of the stationary police patrol with lights or radar on was greater than other methods. They also found that the circulating police car strategy was the least effective among those considered in the study.

Beside conventional enforcement methods, considerable effort has been devoted to photo-radar program evaluation. Chen et al. (2002) studied the effects of the photo-radar program (PRP) on traffic speeds and crash rates in British Columbia (BC). A 22-km stretch of the Vancouver Island portion of Highway 17 (Pat Bay Highway) was selected as the study segment. They evaluated traffic speed and crash rates in locations with and without the influence of a photo-radar program. This corridor had 12 individual photo-radar locations (not active all the time). The photo-radar enforcement program started in April 1996. In active PRP locations, the speed was measured by photo radars. In non-PRP and inactive PRP locations, the speed was measured by loop detectors. The study relied on a before-and–after comparison with a control segment to examine the effects of enforcement on speed and crash rates. In addition to the study period in 1996, they used data from a 2-year period before the enforcement began. The results showed that the BC photo-radar program could reduce speed violations and improve safety not only in PRP locations but also along the enforcement corridor. The authors surmised that drivers adjust their speed along the corridor due to the unpredictable location of active radar sites.

Goldenbeld and Schagen (2005) conducted a before-and-after study to analyze the effects of radar guns on traffic behavior. Their focus was investigating the effects of speed enforcement with radar guns on rural roads in the Dutch province of Friesland. They used 4 years of *after* period data (from 1998 to 2002) and 1 year of *before* period data. They also obtained the crash data going back to 1990 in their before-and-after study for a comparison (control) group. To increase the efficiency and effectiveness of the program by covering higher-risk roads, the program's performance was reviewed every 5 to 6 weeks to adjust the corresponding enforcement methods. The results showed that the average speed, number of violators, and number of road crashes decreased during the enforcement program on both target roads and comparison (control) roads, though larger reductions were observed on the target roads.

The relatively high cost of a suitably qualified and trained manpower, along with technology developments, has motivated agencies to consider automated speed-enforcement techniques. Shin et al. (2009) studied the effects of automated programs with fixed, photo speed-enforcement cameras over 6.5 mi of the Scottsdale Loop 101 in Arizona. They chose a monitoring period of slightly more than 1 year (from 2006 through 2007). Three methods of before-and-after study were used to analyze the results: (1) before-and-after study with comparison group, (2) traffic-flow correction, and (3) empirical Bayes. They collected disaggregate speed data in the monitoring area and aggregated speed data 40 mi downstream of the monitoring area. This aggregated data was used to study the spillover effects. Their results showed a statistically significant reduction in the average speed, speed variance, and total number of crashes. They also raised an important question as to whether the decrease in crash rates was because of the decrease in the average speed and of speed variance or whether it might be attributed to an increase in the drivers' awareness because of the program.

The same location was used by Retting et al. (2008) to analyze the effects of the first implementation of the highly visible fixed speed cameras on a U.S. freeway. They examined the results of an implementation period of 9 months (in 2005) using six camera sites over an 8-mile segment (pilot program). The speed data were collected at three different locations: (1) the study corridor, (2) Loop 101 close to the city of Glendale, and (3) 25 mi west of the study corridor. Five rounds of data were collected. The first round started 2 months before implementation of the enforcement program. The next three were performed during the program (approximately 6 weeks, 5 months, and 8 months into the pilot program). The last round covered 6 weeks after suspending the program. The speed was determined based on the time a vehicle took to pass through a series of sensors. Motorists traveling 11 mph above the speed limit (65 mph) were identified as violators. However, as traffic speeds at the non-Loop 101 sites were not measured during the first three rounds of data collection, additional data were obtained for these sites from the Arizona Department of Transportation (ADOT). The results showed a significant reduction in the number of violations along the enforced corridor and 25 mi west of the study highway. The mean speed decreased from 70 to 65 mph after the enforcement initiation and increased to 69 mph soon after the program was suspended. The average speed remained almost the same on other highways even though public opinion surveys showed widespread concern about this speed-enforcement program.

Thomas et al. (2008) evaluated the effectiveness of the NHTSA's High Visibility Enforcement model in Washington State (Ticketing Aggressive Cars and Trucks, TACT), which started in 2004. Four interstate highway segments, each approximately 25 mi long and with high crash rates, were selected. Two of the segments received TACT media messages, along with increased enforcement, while the other two did not receive more enforcement. Enforcement was applied in July and September 2005, each for a period of 10 days, Monday through Friday from 6 a.m. to 2 p.m. Law enforcement officers riding in commercial motor vehicles (CMVs) observed the unsafe driving maneuvers around them. They recorded the movements around CMVs and used them to analyze the unsafe interactions between CMVs and other vehicles. Their study showed the effectiveness of the TACT pilot project on the four highways with high crash rates.

1.3 DESIGNING A NEW ENFORCEMENT PROGRAM

The studies in the third group focus on designing a new enforcement program. Designing an enforcement study includes considering three major characteristics: spatial distribution, monitoring periods, and number of monitoring stations. Effective design entails finding the best combination of technology and program characteristics to maximize enforcement effectiveness at a given level of resources.

Jorgenson et al. (1999) developed a new speed-monitoring system in the state of Indiana. They followed a systematic selection of appropriate enforcement strategies, using a Delphi process to determine the relative weights for various types of roads and crashes. They employed daily vehicle miles traveled (DVMT), crash distribution, and Indiana DOT's criteria to identify the number of required enforcement sites for each road type. By applying these factors, they determined the number of monitoring stations. They subsequently combined the result of the Delphi method with the number of monitoring sites to propose a spatial distribution for the monitoring stations in the study area.

Waard and Rooijers (1994) were interested in determining the most effective enforcement strategy and the most efficient use of police patrols on Dutch highways. To identify the most effective methods, they analyzed three different variables: intensity of enforcement at three different levels, method of enforcement (on-view stopping vs. mailing fines), and the time delay in mailing the fines. They optimized the police patrol cost by relating the intensity of enforcement to the number of violations. Speed was recorded by loop detectors before, during, and after the enforcement. They used the mean and variance of speed to assess the effectiveness of the enforcement. Their findings showed the impact of the enforcement intensity on the halo effect. They also found that on-view stopping was more effective in reducing the speed limit violation.

In a less direct but quite insightful study, Summala and Naatanen (1980) examined in a series of three experiments the effects of increased police enforcement in Finland by leveraging the occurrence of a police strike (during which police officers step up their enforcement activities). In the first (natural) experiment, the police strike started quite unexpectedly, with almost no warning time to drivers. Historical data were obtained starting about 1 month prior to the program. The second experiment was conducted on one stretch of the road. The speed was measured 4 days a week from 10 a.m. to noon for 2 weeks of the strike and 1 week after it. A third experiment was conducted for 7 days, 3 days of strike, and 4 days after it on a city street. The results showed that the mean and standard deviation of speed decreased. Also, the drivers' response to a parked police car was a decrease in speed during the strike, but their speed increased after the strike. It is noteworthy that the strike was found to have no clear effects on driving under the influence of alcohol.

Vaa (1997) studied the impacts of an increase in police enforcement on two road segments northeast of Oslo, the capital of Norway. The two roads were very similar in weather conditions; they covered different areas; and transfer was impossible between the roads. A group of police officers was invited to plan and perform the enforcement based on their own experience. They employed six monitoring sites on each road. The measurement was taken by radar guns and loop detectors. They considered 2, 6, and 8 weeks for their *before* period, enforcement period, and *after* period, respectively. The speed was measured continuously during the study period. The data were then aggregated for each hour. They used a linear multiple-regression method to capture the effects of police enforcement, traffic density, road geometry, and traffic direction. Their results showed that the enforcement program reduced the average speed by 0.9 to 4.8 km/hr in the study area. They also reported 8 weeks of enforcement spillover.

The National Cooperative Highway Research Program (NCHRP 2012) published a report on automated speed enforcement and red light–running cameras. It is based on a study of four cities (Portland, Oregon; Virginia Beach, Virginia; San Diego, California; and Edmonton, Alberta) that have successful automated speed-enforcement programs. The report provides information on the initiation of the program and its structure and operation, as well as on various success factors for such programs. The authors also pointed out that the main objective of the system should be to reduce the crash rate.

1.4 STUDY OBJECTIVES

The present report describes the results of a study conducted for the Illinois Department of Transportation and the Illinois State Police regarding the effectiveness of various techniques and strategies for speed enforcement using police patrol vehicles along major interstate and state highways. The study addresses these agencies' need for field-validated results regarding various aspects of the impact of various patrolling techniques on enforcement effectiveness.

The study findings are intended to support and inform agency decisions regarding resource allocation for cost-effective enforcement along the state's highway system.

Accordingly, the primary objectives of the study follow:

- Investigate the effects of alternative police patrolling techniques and strategies on the average speed, crash rate, and number of citations
- Identify effective enforcement parameters, such as time of day (morning peak, afternoon peak, and nonpeak) and patrol duration
- Ascertain the existence of the time halo and characterize its properties if applicable
- Provide recommendations on optimal allocation of enforcement resources

This study is the first to investigate the effects of various police patrolling strategies on the average speed, number of citations, and existence and extent of the time halo that may be associated with such strategies under particular conditions. The results provide the basis for a methodology that may be used to allocate optimally the limited enforcement resources in a manner that maximizes the cost-effectiveness of the contemplated deployment.

1.5 STUDY APPROACH AND KEY FINDINGS

To accomplish the objectives of the study, the primary approach is to conduct field experiments in which the effectiveness of various enforcement strategies can be measured and ascertained. To design the field experiments and articulate the principal aspects that warrant investigation (relative to the existing body of knowledge from other states and areas in this domain), two main sources of information are relied upon. First, a comprehensive literature review on various safety-evaluation strategies and methods was conducted. Statistical evaluation and modeling techniques in the field of safety were investigated; and appropriate methods, compatible with the study objectives, were selected. Second, interviews were conducted with ISP representatives to identify the current practice in speed enforcement and particular concerns that may be addressed as part of the study.

Accordingly, a two-stage approach to the fieldwork was followed. First, a pilot study with a limited geographic scope was conducted, followed by a statewide study. The main focus of the pilot study was to identify the effect of various enforcement strategies on the average speed, crash rate, and number of citations. On the basis of the recommendations of the ISP and IDOT, two segments in East St. Louis were selected for this purpose. During the 17 weeks of data collection on the two segments, 7 weeks of active police enforcement were planned. Thus, the respective effects of four different police patrolling methods (i.e., stationary overt, stationary covert, circulating, and chase car) on the average speed, number of citations, and crash rate were studied.

The findings of the pilot study were used to design the statewide study, which expanded the geographic scope of the fieldwork and hence the applicability of the results. The statewide study focused in more depth and in different locations on the effects of different enforcement strategies. Four segments were selected for this phase of the study (one in East St. Louis and three in the Greater Chicago area). The objective of the enforcement in Chicago was to identify the effects of different resource-allocation strategies and to study the time halo. The objective of the enforcement in East St. Louis was to identify the most effective enforcement strategy.

Beyond the qualitative insights and quantitative results obtained as a result of the fieldwork, which can be used by the enforcement agency in planning its operational deployments, the study provides a systematic procedure for incorporating the study findings to allocate optimally the enforcement resources to various patrolling techniques at various locations. For this purpose, a mixed-integer nonlinear optimization model was introduced to select the optimal number of patrolling units to achieve certain objectives given the available resources. Application of the model with selected input based on the study yields specific recommendations for patrol effectiveness.

The main findings of this study can be summarized as follow:

- Enforcement was more effective during the morning peak period in comparison with other periods. Furthermore, the enforcement strategies had the least effect during the afternoon peak periods.
- The enforcement resulted in a greater reduction in average speed during weekends than during weekdays.
- The time halo was found to be at least 2 weeks (time halo is defined as the time until the effects of enforcement on driver speed completely disappear).
- The time halo can be used to reduce enforcement cost. The study findings suggest that using fewer patrol units, while taking advantage of the time halo, could produce virtually the same outcome as employing more patrol units.
- The results of the data analysis revealed that starting with high-intensity enforcement and then progressively lowering the intensity produced a more favorable outcome than starting with low intensity and progressively increasing it.
- The stationary covert strategy was the most effective method, considering the ability to cite violators and reduce the average speed.
- Stationary overt and circulating overt strategies were more effective in reducing the average speed but less effective in citing the violators.
- The sensitivity analysis based on the mathematical programming formulation revealed that it is very important to set appropriate objectives for the enforcement plan.
- It is also recommended that two patrol units be used on the segments to increase the efficiency and effectiveness.

1.6 REPORT ORGANIZATION

This report is organized in six chapters. Following the background review and the description of the study objectives and approach in the present chapter, Chapter 2 describes the pilot study conducted to test the study methodology and obtain the initial information that provided the basis for designing the rest of the fieldwork. In addition to describing the location-selection procedures, the chapter provides a detailed explanation of the experimental design adopted to test and compare the different enforcement techniques. The results of the pilot study are also included in that chapter.

Chapter 3 describes the statewide extension of the study to consider various geographic locations across the state. The process for recommending the additional locations, which used information from the pilot study, is described. The enforcement strategies tested and protocols followed are detailed. The results from the statewide tests are presented in the chapter, along with the principal technical findings.

Chapter 4 presents a comparison of the findings from the pilot study and the statewide tests, identifying areas of agreement and differences.

Chapter 5 builds on the results to formulate a methodology for the optimal allocation of enforcement resources to various patrol strategies to achieve and maximize certain enforcement objectives at given cost levels. The methodology is applied using findings from the field study to provide practical recommendations to the responsible agencies.

Finally, Chapter 6 summarizes the key findings from the study and presents conclusions and recommendations for field application of the results.

CHAPTER 2 PILOT STUDY

This chapter describes the pilot study conducted to test the study methodology and obtain the initial information that provided the basis for designing the rest of the statewide fieldwork. In addition to describing the location-selection procedures and the selected locations, the chapter provides a detailed explanation of the experimental design adopted and the associated methodology followed to test and compare the various enforcement techniques. The results of the pilot study are also included.

2.1 DATA COLLECTION AND INITIAL PROCESSING

The site-selection approach for the pilot study is discussed in detail in this section. In the following sections, the site-selection criteria and their importance are discussed. The selected locations are then introduced and their geometric characteristics described.

On the basis of the recommendations from the Illinois State Police Department (ISP), the city of East St. Louis in St. Clair County was selected for the pilot study. The criteria considered in the site-selection process are as follows:

- Crash rate
- Length of the segments
- Avoidance of construction zones
- Presence of occupancy loop detectors and speed detectors
- Capability of having both overt and covert enforcement
- Existence of a control section similar in characteristics to the study sections

Five crash types (fatal injury, A-injury, B-injury, C-injury, and property damage) were considered for the site selection. The designations A, B, and C refer to the level of injury sustained in the crash, with A referring to the critical injury of at least one person and C referring to only minor injuries. Property damage crashes refer to the crashes with no personal injury. IDOT WebCubeBrowser and IDOT GIS dataset are the two crash-data sources used for site selection. The GIS dataset covers Illinois from 2001 through 2009. By contrast, the WebCubeBrowser covers crashes throughout Illinois from 2005 through 2008 (it contains information on fatal crashes for 2004 as well). Segment length was also considered in addition to the crash rate. A very short segment could reduce the accuracy of the study, while a very long segment would increase the cost. Considering these facts, availability of 6- to 15-mi segments, along with places to perform covert enforcement, were taken into account in the site selection. In addition, the existence of occupancy loop detectors and speed-detection sites were also considered. The St. Louis Metropolitan Area Traveler Information website was used to find the loop detector locations, and the IDOT GIS dataset was used to locate the speed-detection sites. As noted, construction zones were avoided in this study.

On the basis of the above criteria, two highway segments near East St. Louis were selected for the pilot study. Instead of having a long period of enforcement on one segment and having possibly to correct for the cumulative effects of enforcement, two segments were selected for testing over shorter periods. Figures 2.1.1 and 2.1.2 show these two segments; Figures 2.1.3 and 2.1.4 show the crash rates for all five types of crashes on both segments. The figures indicate that crash rates on these two segments were higher than on other highways in the area. It is noteworthy that the crash rate was higher on I-64 compared with I-55/I-70. Figure

2.1.5 shows the current condition of the two segments and the location of loop detectors. In the following sections, these highway segments and their characteristics are discussed in detail.

2.1.1 Segment 1: I-64

This segment is located between North Kingshighway and North Illinois Street (IL 159), with a length of 6 mi (Figure 2.1.1). It has three lanes in each direction with five left and five right curves in the eastbound direction; it also has six overpasses. There are eight detection sites with occupancy loop detectors along this highway segment (four in each direction), and no speed-detection site is located on this highway. Figure 2.1.6 shows all types of crashes for 2001 through 2004 and for 2009 (which were not covered in the W0065bCubeBrowser at the time of the study), and Figure 2.1.8 shows the various types of crashes on this road segment, based on the IDOT WebCubeBrowser data from 2004 through 2009.

2.1.2 Segment 2: I-55/I-70

This segment is located between IL 203 and Vandalia Street (IL 159), with a length of 10.5 mi (Figure 2.1.1). Unlike the I-64 segment, this one does not have a uniform road section; it has three lanes in each direction for 5.5 mi and two lanes in each direction for 5 mi. It has five left and five right curves in the eastbound direction; it also has six overpasses. There are 16 detection sites with occupancy loop detectors on this highway segment (8 in each direction), and no speed-detection site is located on this highway. Figure 2.1.7 shows all types of crashes for 2001 through 2004 and for 2009 (which were not covered in the WebCubeBrowser at the time of the study). Figures 2.1.8, 2.1.9, and 2.1.10 show the different types of crashes on this road segment, based on the IDOT WebCubeBrowser data from 2004 through 2009.

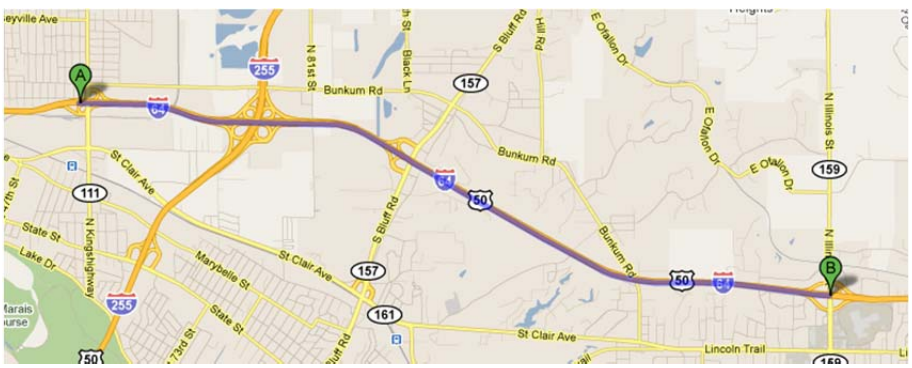


Figure 2.1.1 Study segment on I-64.

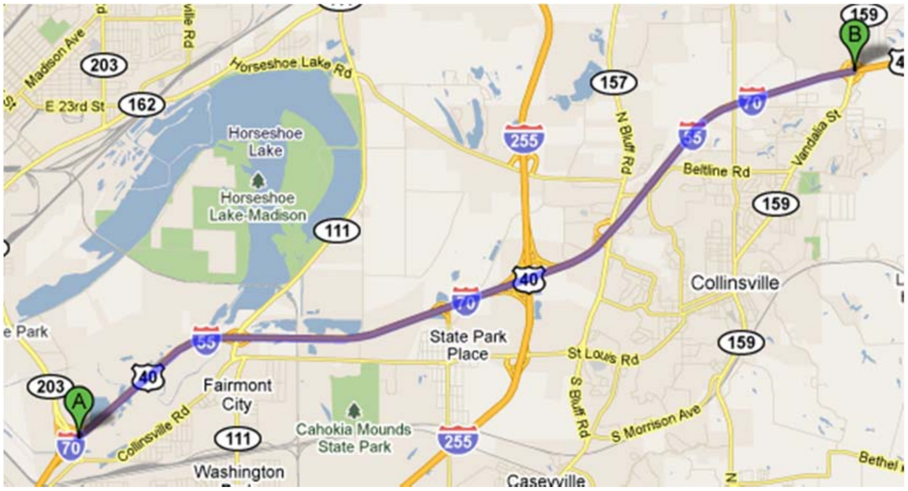


Figure 2.1.2 Study segment on I-55/I-70.

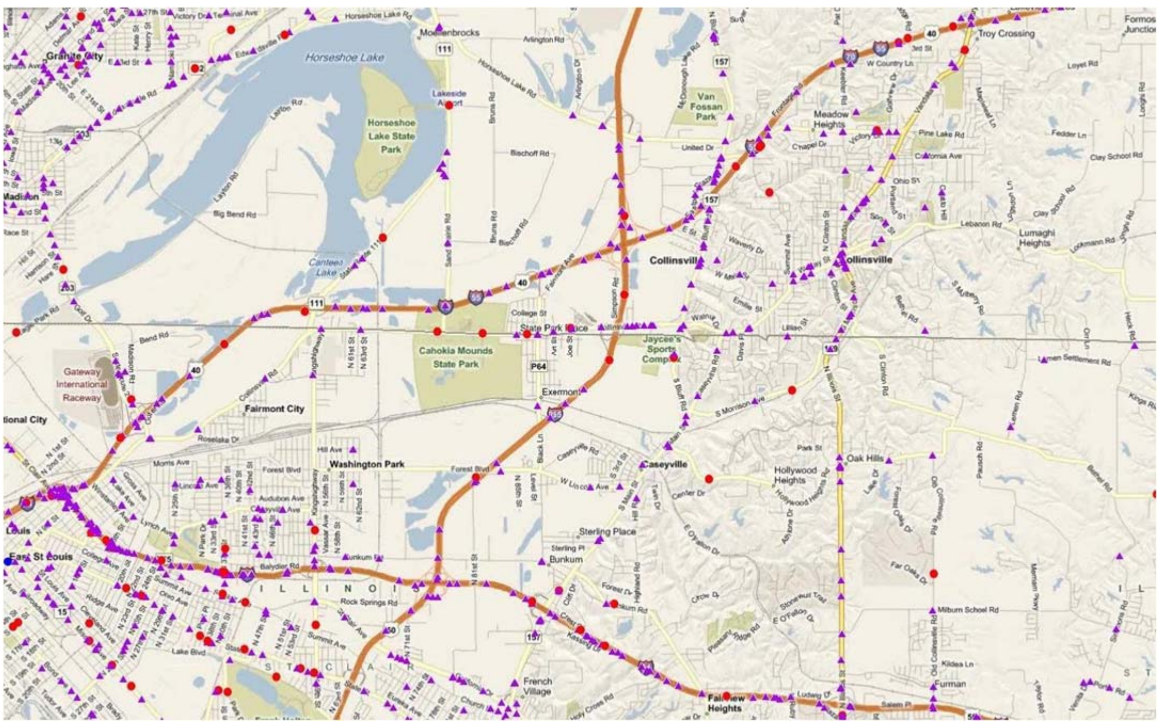


Figure 2.1.3 Fatal and A-injury crashes on I-64 and I-55/I-70 (red circles show fatal crashes, and purple triangles show A-injury crashes). (Source: IDOT WebCubeBrowser)

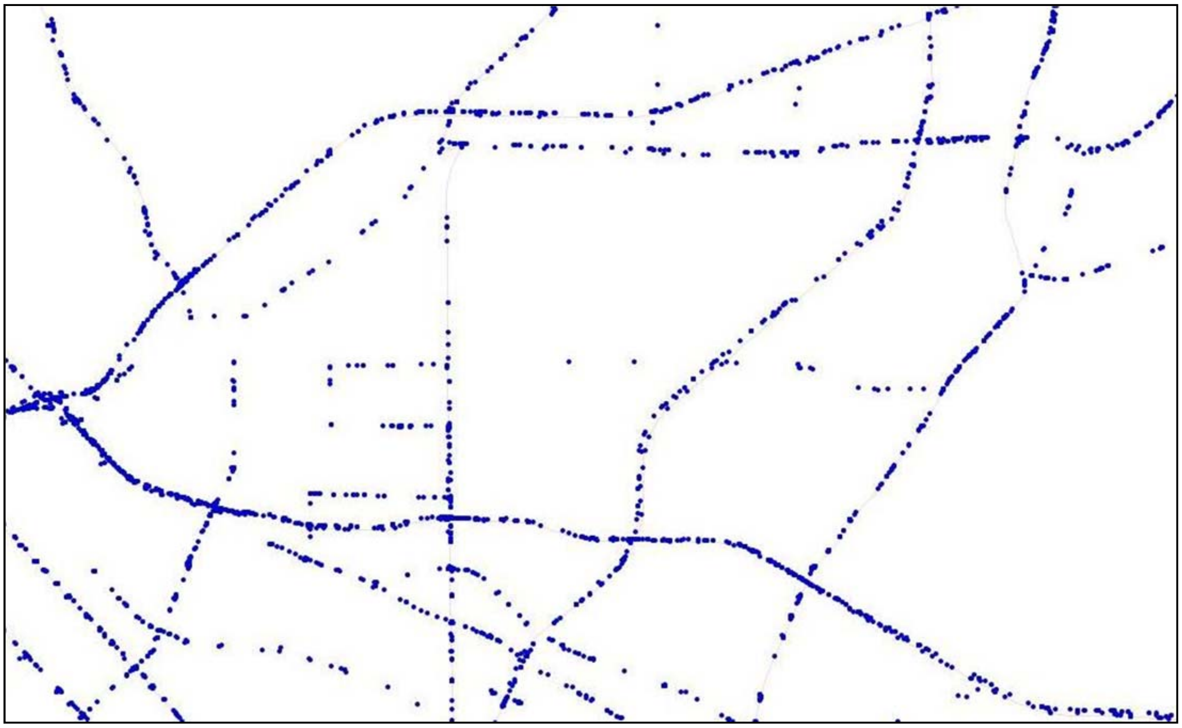


Figure 2.1.4 All types of crashes on I-64 and I-55/ I-70. (Source: IDOT GIS dataset for 2001 through 2004 and for 2009)

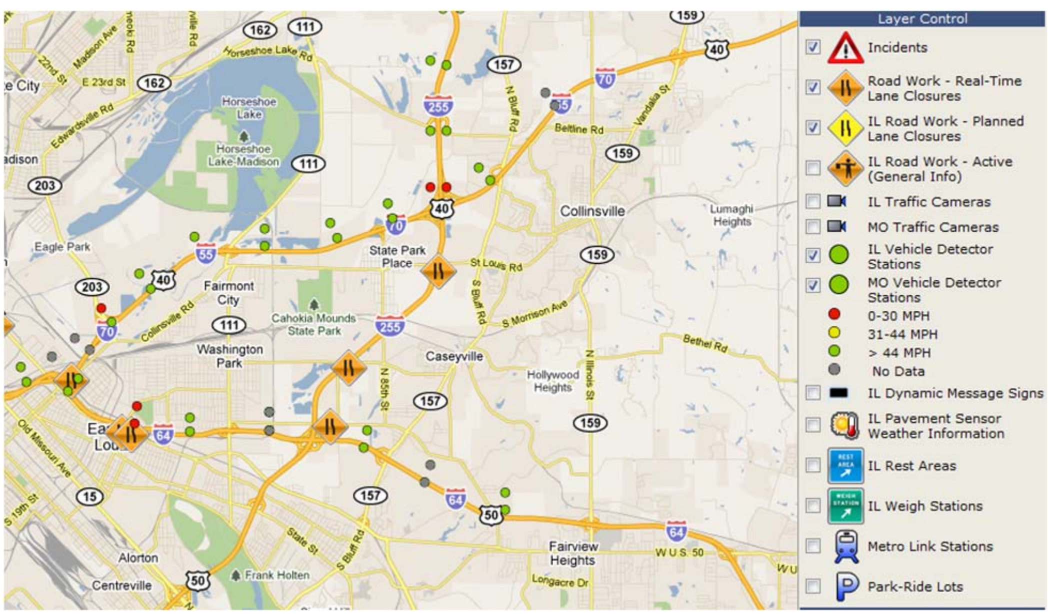


Figure 2.1.5 Condition of the highway segments and location of the loop detectors (at the time of study). (Source: St. Louis Metropolitan Area Traveler Information website)

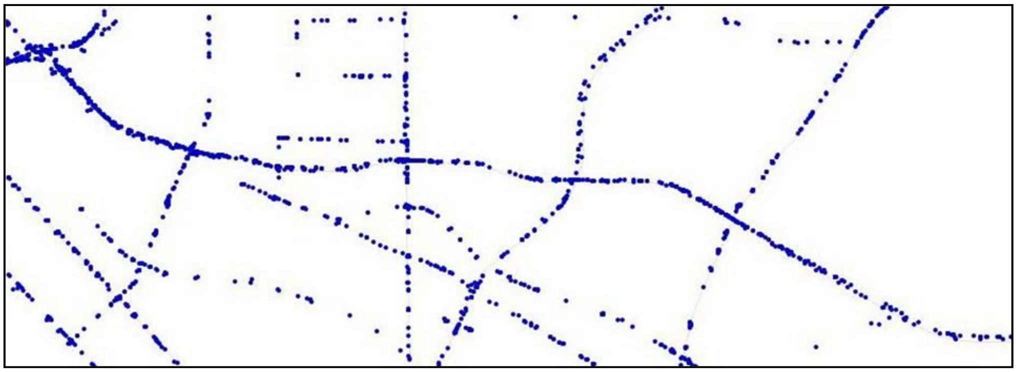


Figure 2.1.6 All types of crashes for 2001 through 2004 and for 2009 for segment 1. (Source: IDOT GIS dataset)

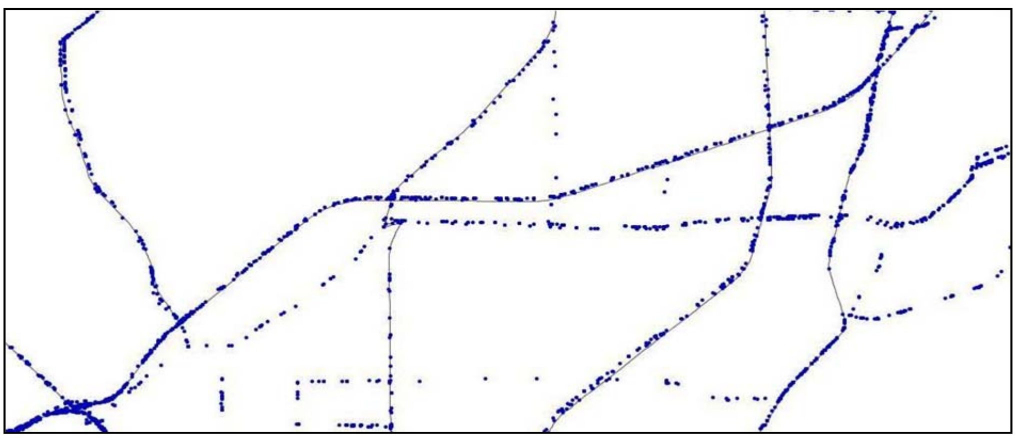
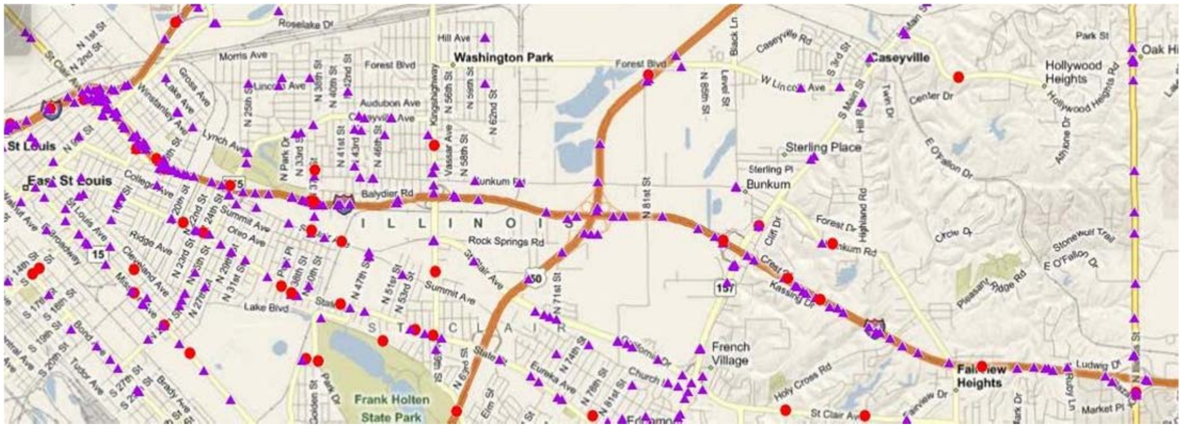


Figure 2.1.7 All types of crashes for 2001 through 2004 and for 2009 for segment 2. (Source: IDOT GIS dataset)

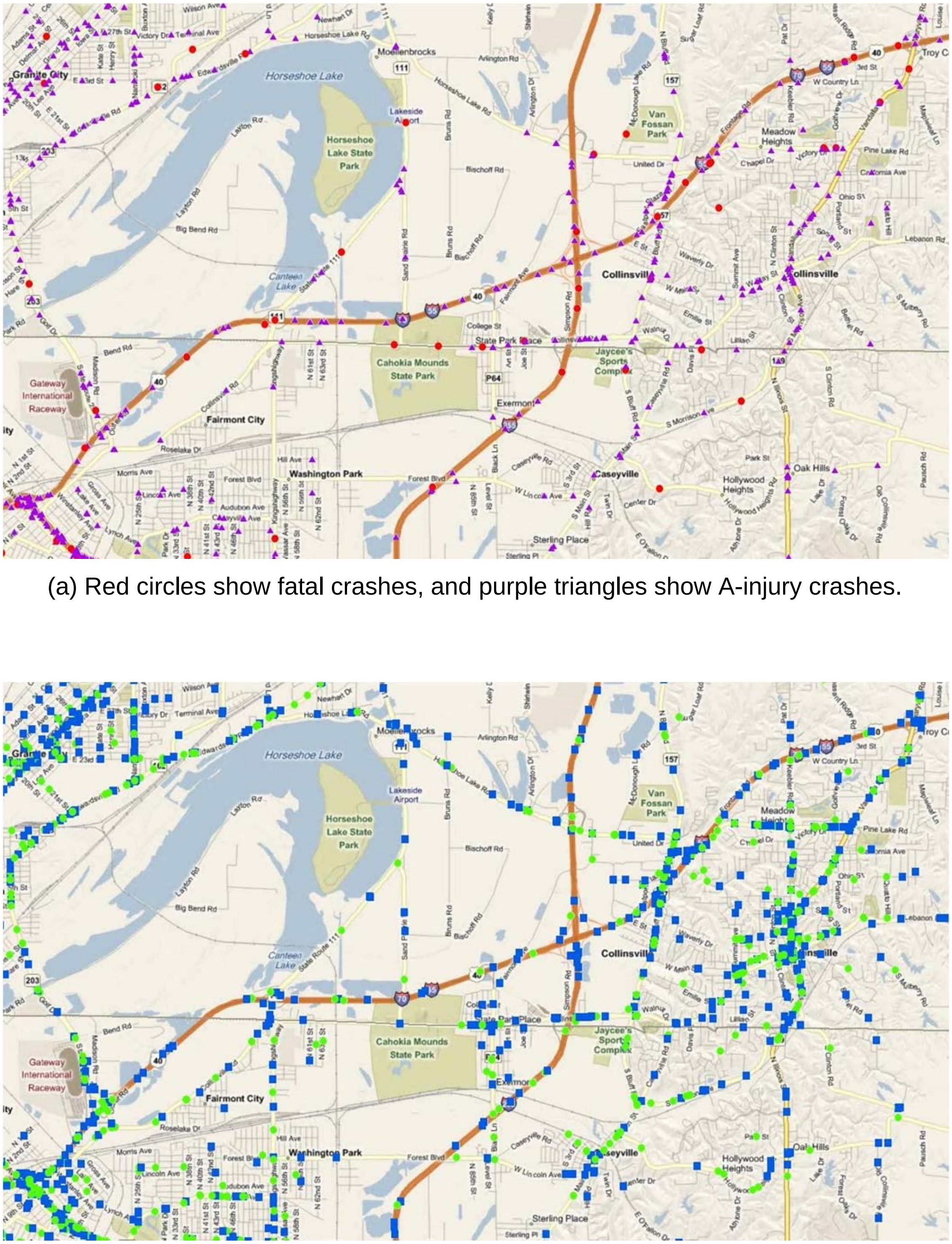


(a) Red circles show fatal crashes, and purple triangles show A-injury crashes.

(b) Blue rectangles show B-injury crashes, and green circles show C-injury crashes.

(c) Property damage

Figure 2.1.8 Various crash types for segment 1. (Source: IDOT CubeWebBrowser)



(a) Red circles show fatal crashes, and purple triangles show A-injury crashes.

(b) Blue rectangles show B-injury crashes, and green circles show C-injury crashes.

Figure 2.1.9 Various crash types for segment 2. (Source: IDOT CubeWebBrowser)

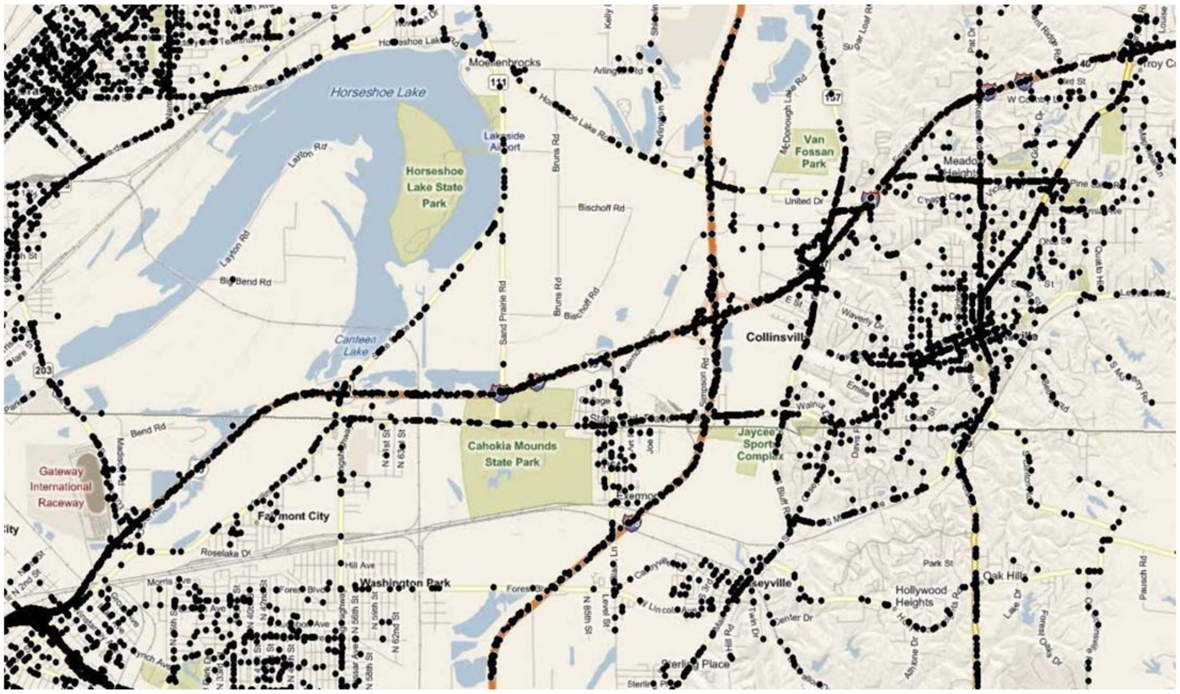


Figure 2.1.10 Property-damage crashes for segment 2. (Source: IDOT CubeWebBrowser)

2.2 ENFORCEMENT STRATEGIES/EXPERIMENT DESIGN

The pilot study was designed to achieve the following goals:

- Study the effectiveness of various types of enforcement
- Investigate the existence and characteristics of possible time halo
- Identify better resource-allocation strategies.

To prevent disruptions in administering the experiments (e.g., due to the limited availability of troopers) and mitigate the possible effect that enforcement on one segment may have on the other segment, the two segments were enforced sequentially. In the following sections, common patrolling methods on a highway segment are discussed; and the selected enforcement strategies on each highway are introduced. Finally, a brief description of the datasets is provided.

2.2.1 Patrolling Method

On the basis of the information obtained from interviewing Illinois State Police (ISP) troopers, various resource-allocation strategies and patrolling methods were identified. The main factors for resource allocation are as follows:

- Enforcement duration at a given highway segment (hours)
- Platoon size at a given highway segment (number of officers)
- Coverage area (miles)

More coverage, more patrolling hours, and a smaller platoon size may reduce the effectiveness of the enforcement and increase its cost. Note that the main limiting factor in this study was the platoon size.

For the purpose of enforcement, either one officer or a group of two to four officers could be assigned to a highway segment. When only one officer patrols a segment, he/she may remain stationary at a point on the highway until catching a speeding vehicle (traffic stop). The officer changes the detection position after each traffic stop, moving in the direction of traffic until reaching the end of the segment. Thereafter, the officer moves to the opposite direction and enforces the traffic speed along the new direction. While moving, he/she may detect violators if the police vehicle has the appropriate equipment. Such equipment gives the officer the ability to circulate along the chosen segment. The circulating method can also be employed by a group of officers. Note that in this method, an officer may also detect violators moving in the opposite direction. With a group of officers, the following strategies could be implemented:

- Strategy 1: Officers could distribute themselves evenly in the same traffic direction along a segment (Figure 2.2.1). This type of patrolling is more effective during the daytime with directional traffic (during peak hours or holidays).
- Strategy 2: Officers could stay at the two ends of a segment and monitor the upstream of the segment (Figure 2.2.2). This strategy is effective only when police vehicles can stay completely covert.
- Strategy 3: A similar strategy can be applied for the downstream traffic, when officers stay at the two start points of a segment (Figure 2.2.3). This method is the most common and is more effective for long segments.
- Strategy 4 (Chase car): In this patrolling method, one officer stays on an overpass to detect the violators; and another officer chases the violators one by one.

Regardless of the strategy followed, officers try to maintain a certain distance from each other to increase the enforcement efficiency. As a result, when an enforcement unit changes its position, other units also change their positions either by moving forward in the direction of traffic or by circulating. Other factors that affect the patrolling strategies are the weather, time of the day (morning and evening peak, and off-peak hours), the season, and the various speeding patterns on weekdays, weekends, and holidays.

2.2.2 Pilot-Study Enforcement Strategies

The enforcement strategies for this study have been selected in consultation with the Illinois State Police (ISP). Tables 2.2.1 and 2.2.2 (all tables in this report are in the appendix) show the selected patrolling strategies on each segment. Both segments had no enforcement during their first week, which provides a base reference point for analyzing the effects of enforcement on the average speed. No enforcement was also applied during weeks 4 and 13 to reduce the cumulative effect of continuous enforcement. This design also helped us study the possibility of using the time halo to maintain the average speed at a reasonable value, rather than conducting continuous enforcement. Note that the enforcement on I-55/I-70 was started after I-64 because of limitations on the number of troopers available for the study.

Various combinations of one, two, and four officers were used to increase or decrease the intensity of the enforcement. The selected enforcement strategies are as follow:

- Circulating
- Stationary overt
- Stationary covert
- Chase car

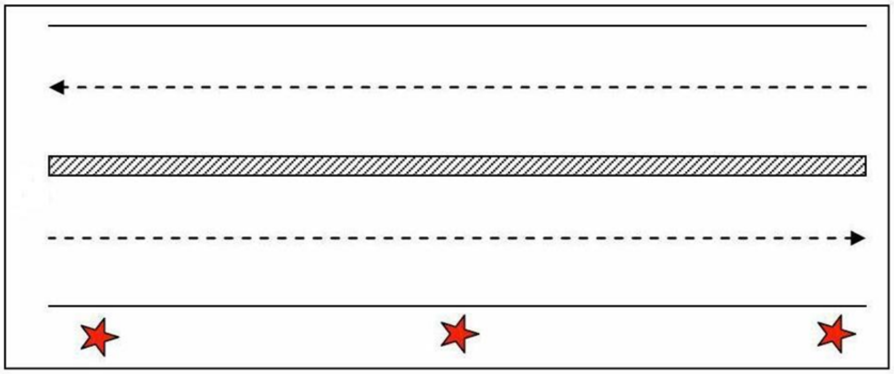


Figure 2.2.1 Evenly distributed enforcement units along the segment.

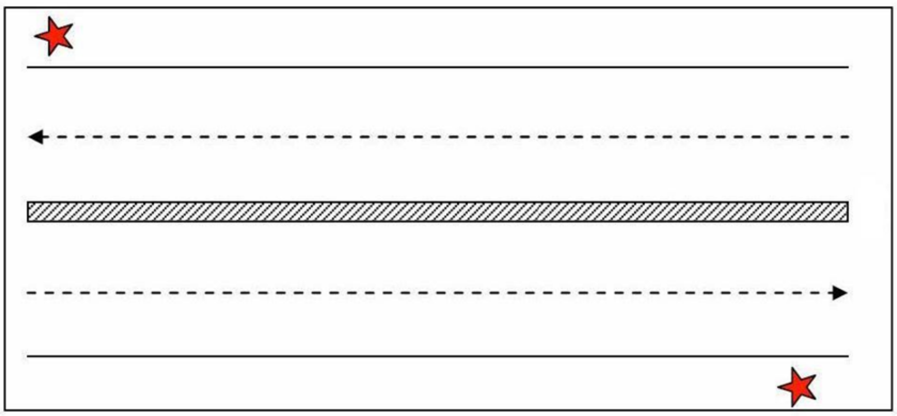


Figure 2.2.2 Monitoring upstream of the segment.

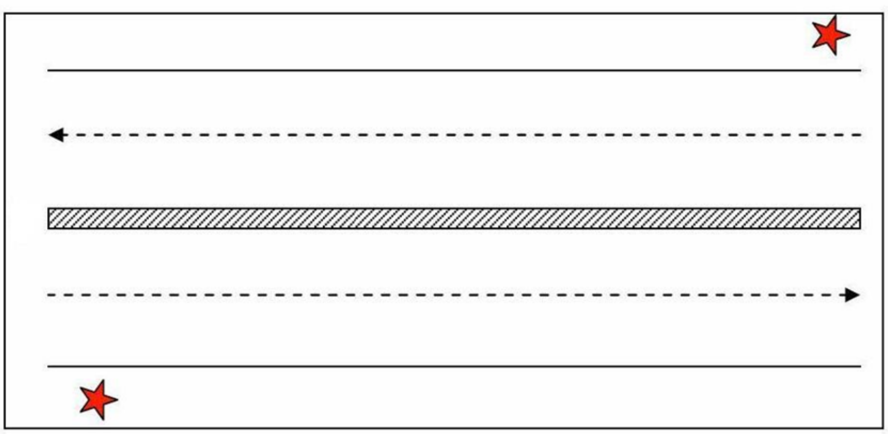


Figure 2.2.3 Monitoring downstream of the segment.

The circulating strategy was performed during the first 2 weeks of enforcement on I-64. This strategy gave us the opportunity to study the cumulative effect of continuous enforcement on the average speed. Those 2 weeks were followed by a week with no enforcement, to reduce the effects of continuous enforcement on driving behavior. The enforcement was resumed after that week (fourth week) by implementing the stationary overt strategy, followed by a week (fifth week) of circulating overt enforcement. However, this time only one patrolling unit was involved. This strategy was selected to compare the effectiveness of two patrolling units with one patrolling unit.

The first week of enforcement on I-55/I-70 started with a test of the effectiveness of the stationary covert strategy in reducing the average speed. This week was followed by a week of high-intensity enforcement with four patrolling units using the circulating overt strategy. This high-intensity enforcement provided an opportunity to study the relationship between any possible speed reduction and the number of troopers. The chase car strategy was selected for the last week of enforcement on this segment. This method is not very common, but it is useful to compare its results with those obtained with other methods. Finally, 3 weeks of no enforcement were monitored at the end of the enforcement period on each segment to investigate the existence of the time halo.

To capture the details of the enforcement implementation, a form was designed to collect the information regarding the patrolling location, patrolling hours, number of citations issued, weather conditions, and patrolling vehicle. This form is presented in Figure 2.2.4.

2.2.3 Brief Description of Datasets

Dataset 1 was collected from the occupancy loop detectors on I-64. The location of the detectors is presented in Figure 2.1.5. The speed data are available in 1-minute intervals. The planned enforcement on this segment started at 6 a.m. and continued for 12 hours. The enforcement on this segment started on June 27, 2011, after 1 week of no enforcement. The last day of enforcement on this segment was July 31, 2011. After this date, 3 weeks of no enforcement started. Dataset 2 was collected from the occupancy loop detectors on I-55/I-70. The location of the detectors is also presented in Figure 2.1.5. The speed data are available in 1-minute intervals. The planned enforcement on this segment started from 6 a.m. and continued for 12 hours. The enforcement on this segment started on August 29, 2011, after one week of no enforcement. The last day of enforcement on this segment was September 25, 2011. After this date, 3 weeks of no enforcement started.

ICT-R27-66 Effectiveness of Innovative Speed Enforcement Techniques in Illinois

Daily Patrol Result

Illinois Department of Transportation   Illinois State Police   Northwestern University

Officer ID ____________________   Date: / / 2011

Location: I-64 ☐ I-55/I-70 ☐

Direction: Eastbound ☐ Westbound ☐

Start Time: ------ : ------ (am/pm)

End Time: ------ : ------ (am/pm)

Number of Speeding Tickets: ____

Number of Speeding Warnings: ____

Number of Accidetns / Types: ____________________

Type of Strategy:

☐ Circulating Overt

☐ Stationary Overt

☐ Stationary Covert

☐ Chase Car

Weather:

☐ Clear

☐ Rainy

Patrolling Vehicle: Car ☐ Motorcycle ☐

Hourly Report:

(Check each box if you patrol at the corresponding period)

6:30 - 7:30	7:30 - 8:30	8:30 - 9:30	9:30 - 10:30	10:30 - 11:30	11:30 - 12:30	12:30 - 13:30	13:30 - 14:30	14:30 - 15:30	15:30 - 16:30	16:30 - 17:30	17:30 - 18:30

Figure 2.2.4 Daily patrol result form.

2.3 METHODOLOGY

The effectiveness of each enforcement strategy was evaluated from the following standpoints: average speed and number of citations. The average speed for each treatment was calculated based on 1-minute average speed data obtained from the loop detectors in the study segments (Figure 2.1.5). The average speed for every 1 minute of active enforcement was calculated using the arithmetic mean of speed among the working loop detectors' data. The averaging approach was selected because of the unknown location of patrolling unit(s) on the study segments. This approach could in fact help determine the effects of each enforcement strategy on the whole segment. The arithmetic averaging method was selected because the volume data was not available.

It is also important to note that the actual enforcement did not completely follow the planned enforcement schedule. Limited availability of troopers, accidents, troopers' maximum working hour restrictions, arrests, and other unplanned incidents were the main reasons for this discrepancy. These periods were excluded from the analysis. The periods with inclement weather conditions (i.e., heavy rain) were also excluded from the analysis. These periods are shown in Tables 2.3.1 and 2.3.2 as white cells.

The arithmetic mean was calculated for the morning peak period (6 to 10 a.m.), the off-peak period (10 a.m. to 4 p.m.), part of the afternoon peak period (4 to 6 p.m.), and the whole active enforcement period (6 a.m. to 6 p.m.). These values are then compared with their corresponding values from other days and weeks using t-tests and Wilcoxon rank-sum tests to find the effects of different enforcement strategies on the average speed. Note that t-test assumes the normal distribution, while the Wilcoxon rank-sum test is a nonparametric test with no assumption on the distribution.

In addition to the average speed analysis, the enforcement strategies were compared based on the number of citations. It is expected that the enforcement strategy that captures more violators performs better. However, from the speed-reduction standpoint, the enforcement strategy might cite fewer violators because of its effectiveness in reducing the individual speeds. To overcome this contradiction, the number of citations and the average speed were considered in one equation.

$$Normalized\ Number\ of\ Citations\ (NNC) = \#\ of\ tickets\ and\ warnings\ \times \frac{Average\ speed\ of\ the\ base\ case}{Average\ speed\ of\ the\ treatment} \tag{2.3.1}$$

Higher values of NNC are favorable. Note that to have a fair comparison, the average number of tickets and warnings per patrolling unit were also compared for various strategies.

In addition to the effects of various enforcement strategies on the study segments at the time of enforcing, the temporal effects of each enforcement strategy were also studied. The temporal (halo) effect of the enforcement indicates the sustainability of the enforcement effects over time after removal of enforcement. To study this effect, the data collection was continued for at least 3 weeks after the removal of enforcement along each segment.

2.4 EFFECTS AT TREATMENT LOCATIONS

The effects of each enforcement strategy on the average speed are discussed in this section. It is generally accepted that driving behavior is not the same for weekdays and weekends, and it may even be different for different times of the day. To have a better understanding of the effects of various enforcement strategies on the average speed, a separate analysis is presented for weekdays and weekends, as well as for morning peak hours, nonpeak hours, and afternoon/evening peak hours. In the following sections, the effects of enforcement strategies on the two segments during different periods are discussed separately.

2.4.1 Study Segment: I-64 (Weekdays)

2.4.1.1 Morning Peak Period

The interval between 6 and 10 a.m. was considered the morning peak period in the analysis. Figure 2.4.1 shows the average speed during this period for the first three Mondays. The discontinuity in the data in the second week was due to the lack of active enforcement on the segment. This figure clearly shows the reduction in average speed resulting from the enforcement. Figure 2.4.2 also shows the average speed during the same period for the first three Thursdays. This figure clearly shows the effects of the enforcement on the average speed and, more importantly, on the speed variance (also reduced). The speed variance, considering the data between 8 and 10 a.m., was 1.33 for the first Thursday; it decreased to 0.68 and 0.52 on the second and third Thursdays, respectively. The daily and weekly average speeds on this segment are presented in Figure 2.4.3. This figure clearly shows the effects of enforcement on the average speed. In addition, a slight increase in the average speed after stopping the enforcement can be noted in this figure. Thus the effect of continuous enforcement on the average speed reduction can be either positive or negative. Different driving environments (e.g., driver characteristics, traffic conditions, weather conditions), as well as different enforcement intensities, are expected to be the main reason for this observation. Statistical tests, namely t-tests and Wilcoxon rank-sum tests were performed to assess whether the observed differences in the average speeds are statistically significant.

Table 2.4.1 shows the results of the t-tests for the weekly average speed during the morning peak period. The average speed of the *before* period (week 1) was higher than the average speed during the enforcement. In addition, the differences are statistically significant. This finding indicates the positive effect of the enforcement chain on reducing the average speed. However, Figure 2.4.3 shows that the average speed in the third week was higher than the average speed on the second week. Low average speed on the first day of that week was the main reason for this difference. Excluding that day from the calculations, the results show that the average speed in the second week is not statistically different from the average speed in the third week (the t-test value would be –1.93).

Because no enforcement was planned during the fourth week, the average speed increased slightly during that week. After the enforcement resumed in the fifth week, the average speed experienced a decrease in value. The difference in average speed between the fifth and sixth weeks is not statistically significant (the t-test value is 1.17). On the basis of this observation, the time halo can be used to reduce the enforcement cost. Thus, with fewer patrolling units being used, the time halo might produce the same outcome as employing more patrolling units. In the seventh week, after the last week of enforcement, a statistically significant increase in average speed occurred. The same pattern was observed for the eighth week. However, the average speed started to decrease during the last week for an undetermined reason. The results of the Wilcoxon rank-sum test (Table 2.4.2) also reveal a pattern similar to that of the t-test. Figure 2.4.4 illustrates the cumulative speed distributions for the first 9 weeks on I-64. The Kolmogorov-Smirnov test was used to check whether the differences between the distributions are statistically significant (see Table 2.4.3). The results reveal that the enforcement had a statistically significant effect on the average speed distributions.

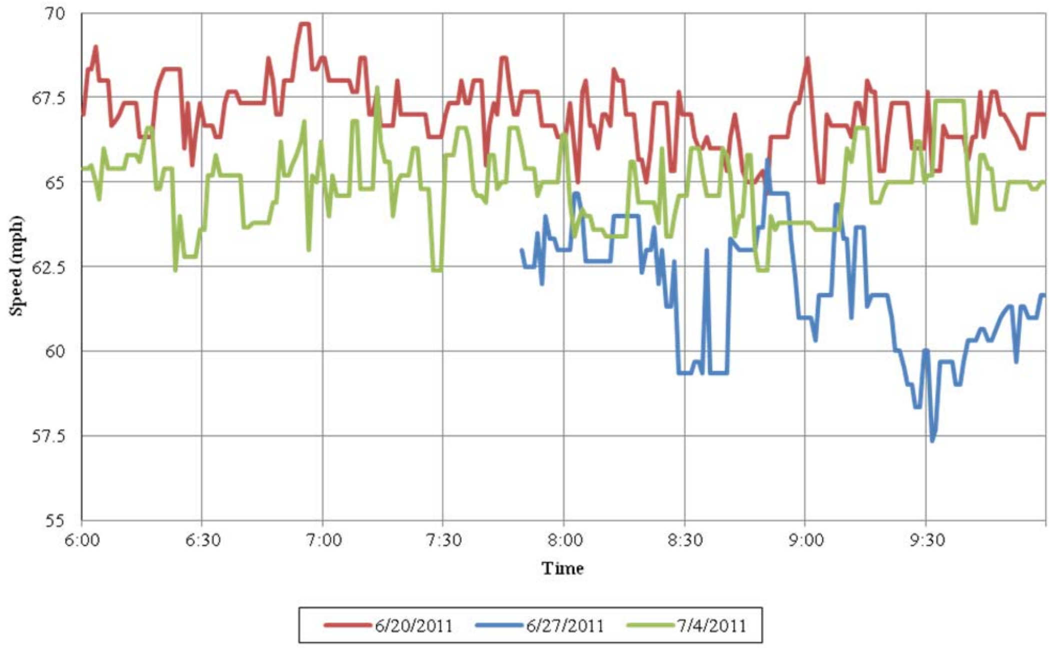


Figure 2.4.1 Average speed during the morning peak hours for the first three Mondays.

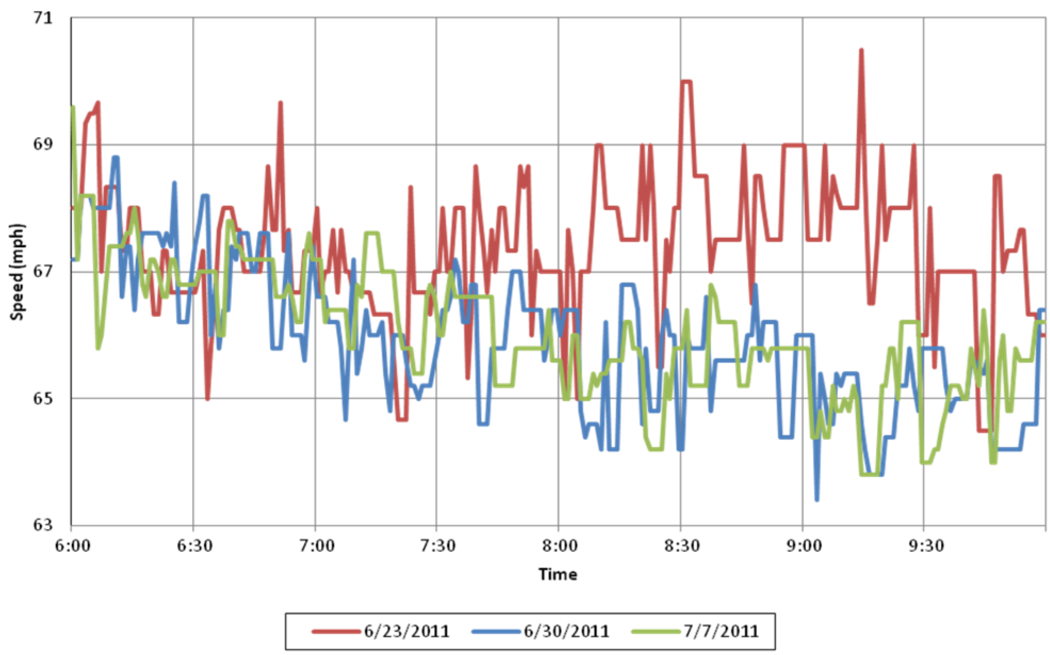


Figure 2.4.2 Average speed during the morning peak hours for the first three Thursdays.

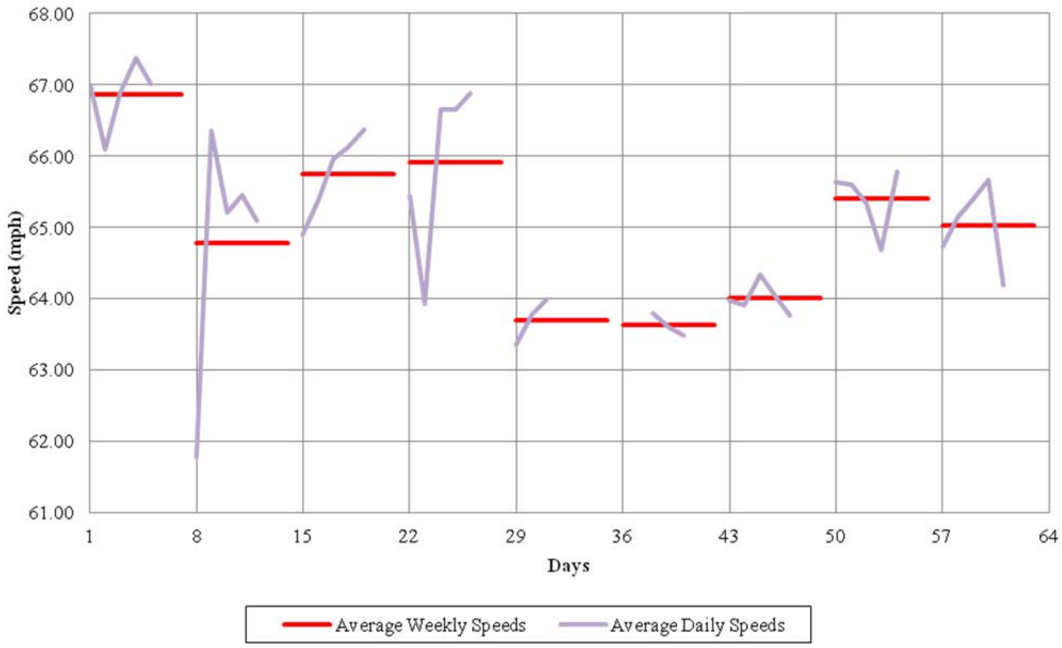


Figure 2.4.3 Daily average speed and weekly average speed during the morning peak hours for 9 weeks of enforcement on I-64.

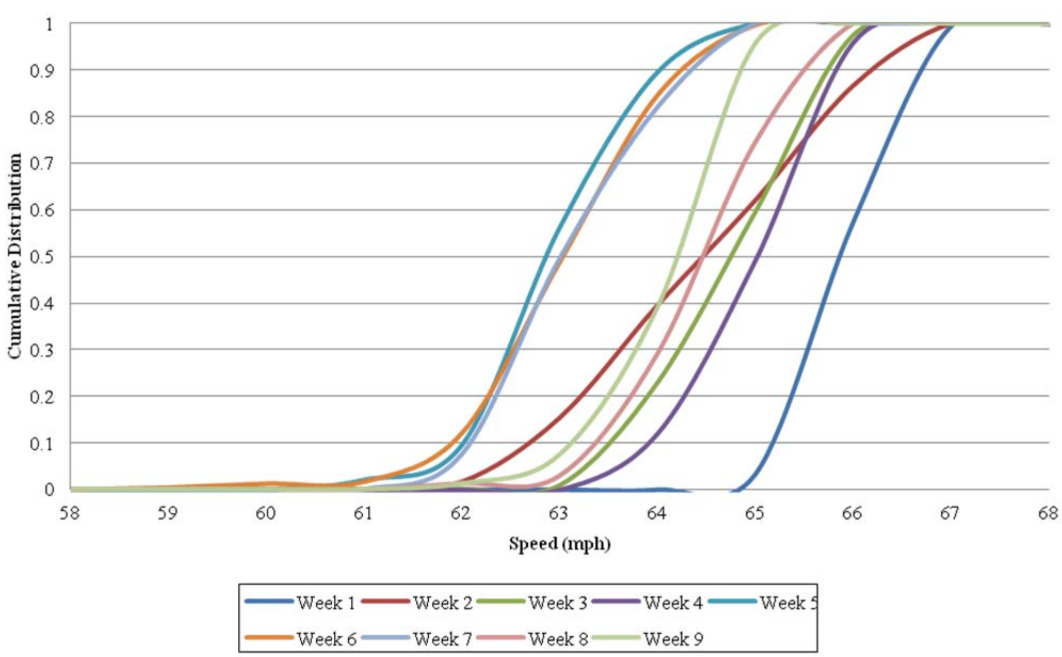


Figure 2.4.4 Cumulative speed distribution for 9 weeks of enforcement on I-64 during the morning peak hours.

2.4.1.2 Nonpeak Period

The interval between 10 a.m. and 4 p.m. was considered the nonpeak period in the calculations. The driving behavior in this period is not similar to the morning peak period; drivers are not in a rush, and the highway is less crowded. The enforcement is expected to have less impact on the average speed and speed variance during this period. Figure 2.4.5 shows the speed during the nonpeak hours for the first three Fridays. On the basis of the figure, we can say the enforcement reduced the average speed. However, the amount of this reduction was less than for the morning peak period (compare this figure with Figures 2.4.1 and 2.4.2). In terms of speed variance, the enforcement had a positive effect on reducing its value from 1.41 on the first Friday to 0.53 and 0.73 on second and third Fridays, respectively. Smaller variance is an indicator of a safer driving environment.

The daily and weekly average speeds during nonpeak hours are presented in Figure 2.4.6. Table 2.4.4 shows the t-test results for this data during the nonpeak hours. The effects of enforcement on reducing the average speed can be recognized by comparing the average speed of the first week with that of the second week. However, the average speed of the third week did not follow the expected pattern. Less enforcement coverage during this period (see Table 4.1) and driving behavior during the nonpeak hours are the main reasons. In the fifth week and after the enforcement resumed, the average speed had a statistically significant drop compared with the previous weeks. This decrease occurred despite the fact that the enforcement coverage was very limited during the fifth week. A similar pattern was observed during the sixth week; and even though the amount of reduction is not very large, the difference is statistically significant. The difference between the average speed during the sixth and seventh weeks is not statistically significant even though the enforcement was terminated after the sixth week. This observation is a clear indicator of the time halo. The average speed started to increase during the eighth and ninth weeks. However, the average speed during the ninth week is lower than the average speed during the first week, which suggests that the time halo of this enforcement program was longer than 3 weeks.

Table 2.4.5 shows the Wilcoxon rank-sum test results. On the basis of this test, all the differences in the average speeds are statistically significant except the difference between the second and fifth weeks. As shown in Table 2.4.5, the difference between the average speed in the seventh and sixth weeks is statistically significant. This speed reduction from the sixth week to the seventh week was not expected. The low average speed on the last day of that week was the main reason for this difference. Excluding that data from the calculations, the results show that the average speed in the seventh week is slightly more than the average speed in the sixth week. The t-test and Wilcoxon rank-sum test show that the difference in the average speeds during the sixth and seventh weeks is statistically significant.

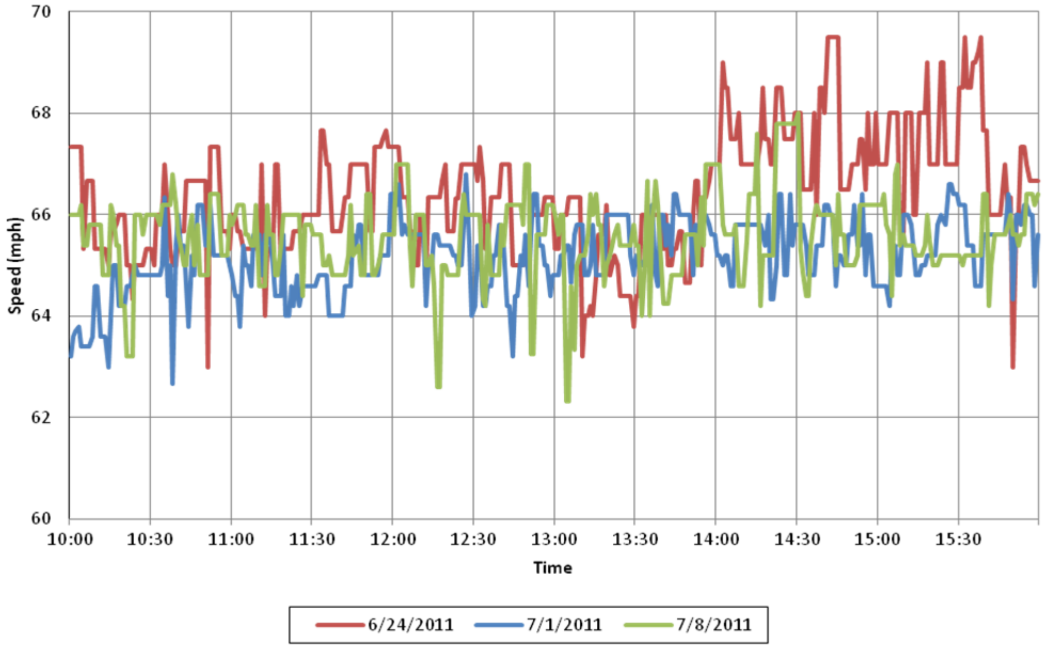


Figure 2.4.5 Average speed during the nonpeak hours for the first three Fridays.

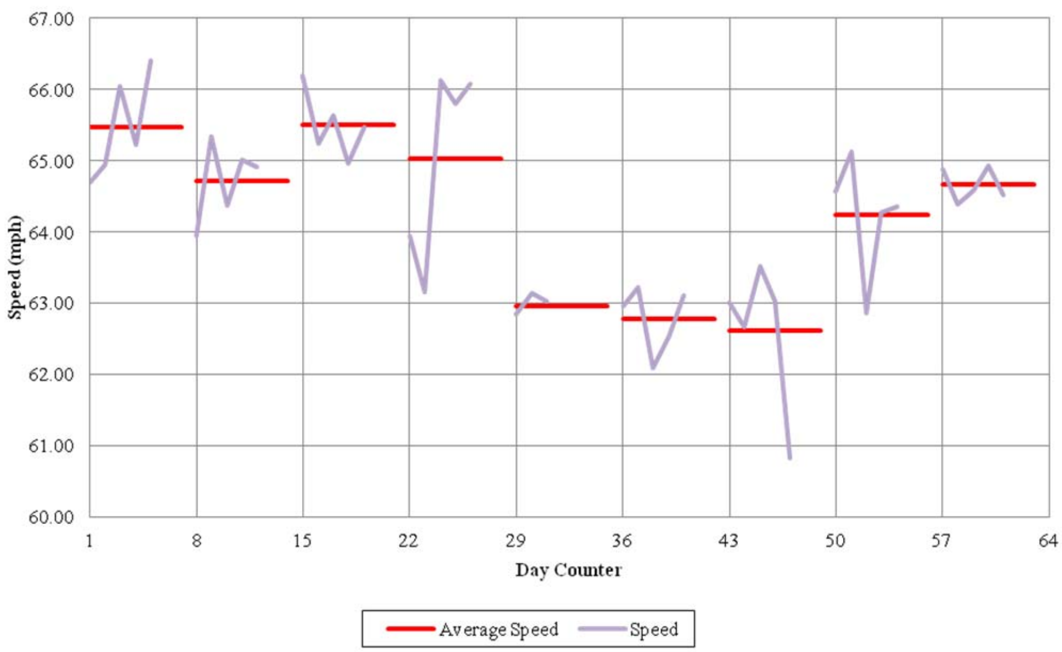


Figure 2.4.6 Daily average speed and weekly average speed
during the nonpeak hours for 9 weeks of enforcement on I-64.

Figure 2.4.7 presents the cumulative speed distributions for the first 9 weeks on I-64. The cumulative distributions clearly show the effects of enforcement during the fifth and sixth week (the corresponding curves are clearly in the left-hand side of the other cumulative distribution curves). Table 2.4.6 shows the Kolmogorov-Smirnov test results for these distributions. The P-values are all very small, which shows the statistically significant difference between all of the distributions.

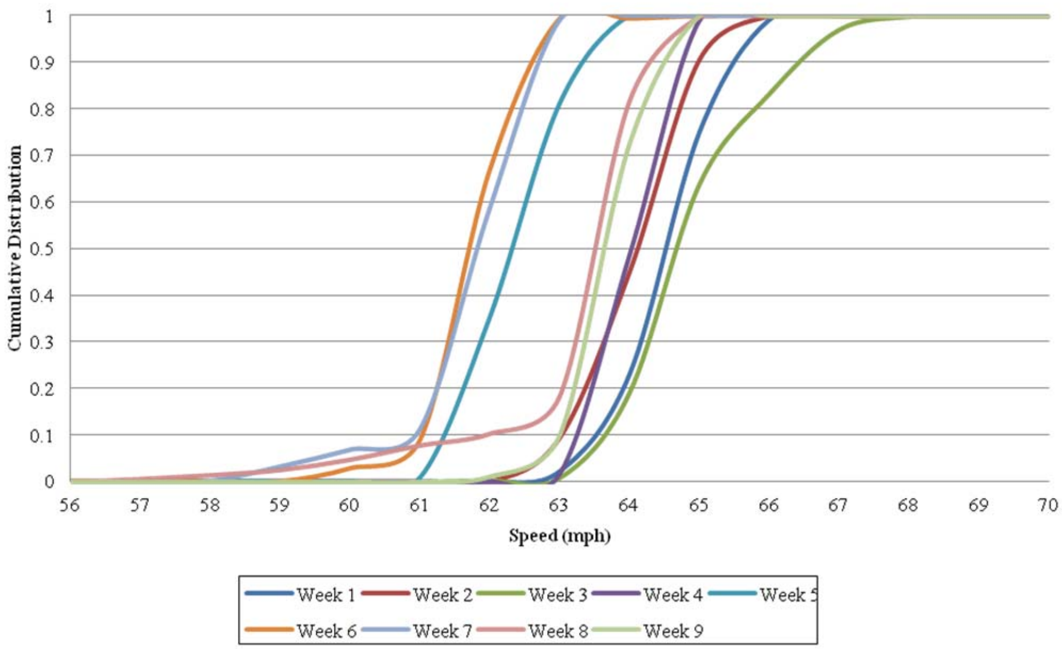


Figure 2.4.7 Cumulative speed distribution for 9 weeks of enforcement on I-64 during the nonpeak hours.

2.4.1.3 Afternoon Peak Period

The interval between 4 and 6 p.m. was considered the afternoon peak period in the calculations. Figure 2.4.8 shows the speed during the afternoon peak hours for the first three Tuesdays. The figure clearly reveals that the enforcement did not have a significant effect on average speed during the afternoon peak hours. However, the variance is reduced from 1.23 in the first Tuesday, to 0.43 and 0.66 in the second and third Tuesdays, respectively.

The daily and weekly average speeds during the afternoon peak hours are presented in Figure 2.4.9. Table 2.4.7 shows the t-test results for this data. The figure indicates that the average speed during the first week had a lower value in comparison with the morning peak and nonpeak periods. This means that the traffic conditions forced the drivers to keep their speeds lower, and the enforcement strategies could not be very effective. However, the enforcement still had positive effects on the variance.

The first 4 weeks of the study had almost the same average speeds; the differences between them are not statistically significant, as shown in Table 2.4.7. The only statistically significant difference is between the average speed during the second week and the average speed during the other 3 weeks. In week 5, after the enforcement resumed, the average speed had a statistically significant decrease in comparison with the previous weeks. The average speed slightly decreased again during week 6, and the difference is statistically significant, based on the t-test value. On the basis of this observation, the time halo can be used to reduce the enforcement cost, in that using fewer patrolling units and taking advantage of the time halo could produce the same outcome as employing more patrolling units. The speed pattern during the last 3 weeks of the study period showed some sort of breakdown formation and a significant reduction in the average speed. The study of the time halo is prevented by this phenomenon. Note that the Wilcoxon rank-sum test results presented in Table 2.4.8 are consistent with the t-test results.

Figure 2.4.10 shows the cumulative speed distributions for the first 9 weeks of study on I-64. Table 2.4.9 presents the Kolmogorov-Smirnov test results for these distributions. The Kolmogorov-Smirnov test results confirm that the cumulative distributions during the first 4 weeks are not statistically different. A significant decrease in the average speeds during the fifth and sixth weeks are also obvious in Figure 2.4.10. The average speed distribution during the sixth week was slightly on the left-hand side of the average speed distribution during the fifth week. This pattern confirms the slightly lower average speed associated with this week in Figure 2.4.9.

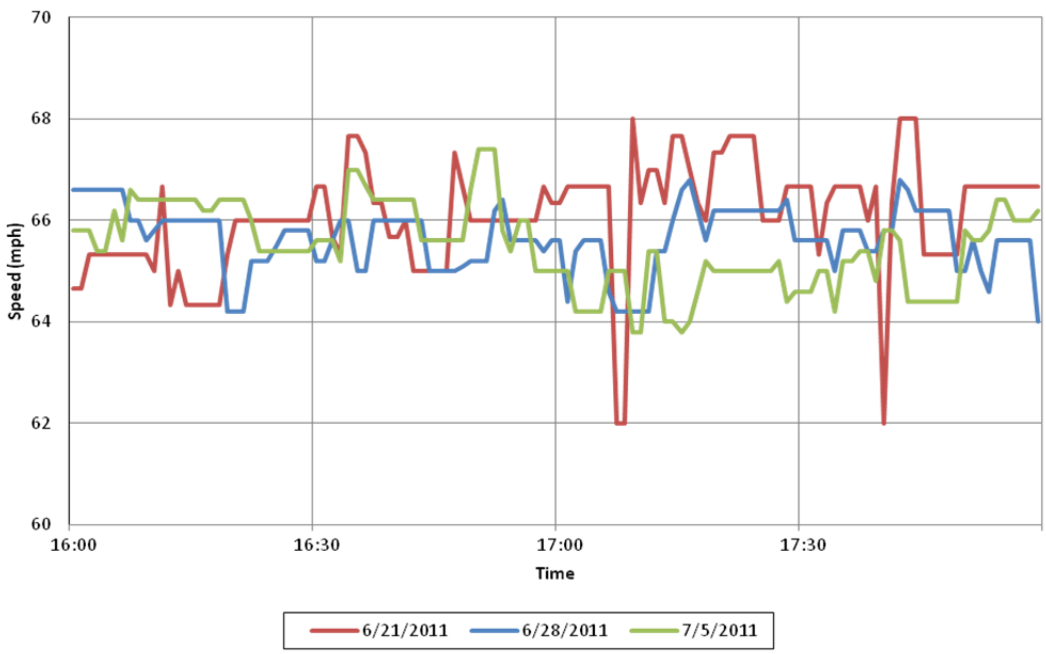


Figure 2.4.8 Average speed during the afternoon peak hours for the first three Tuesdays.

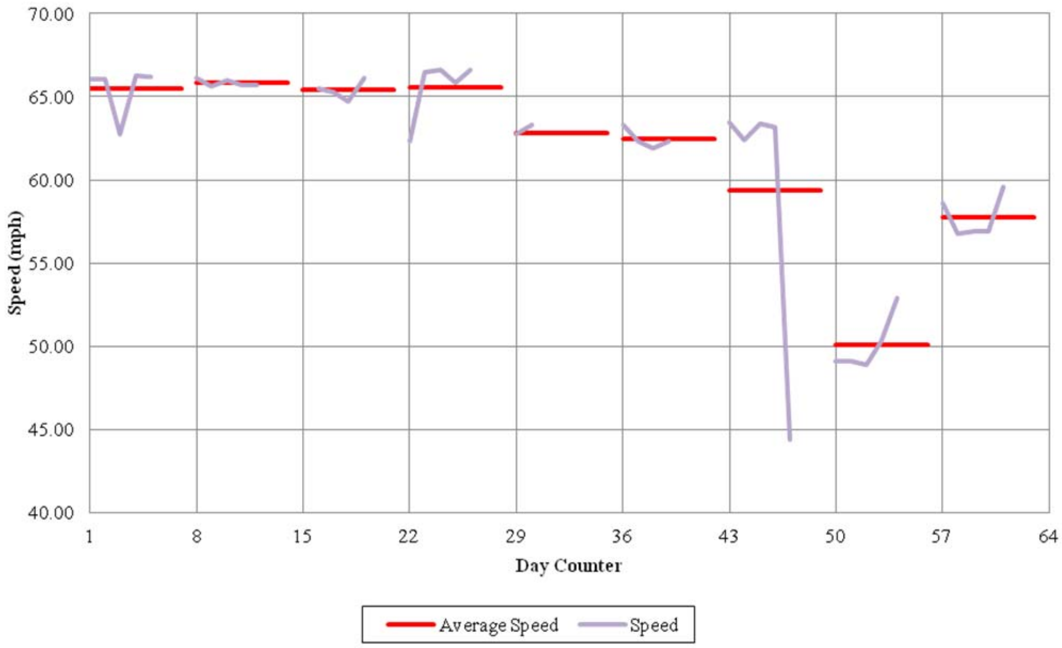


Figure 2.4.9 Daily average speed and weekly average speed during the nonpeak hours for 9 weeks of enforcement on I-64.

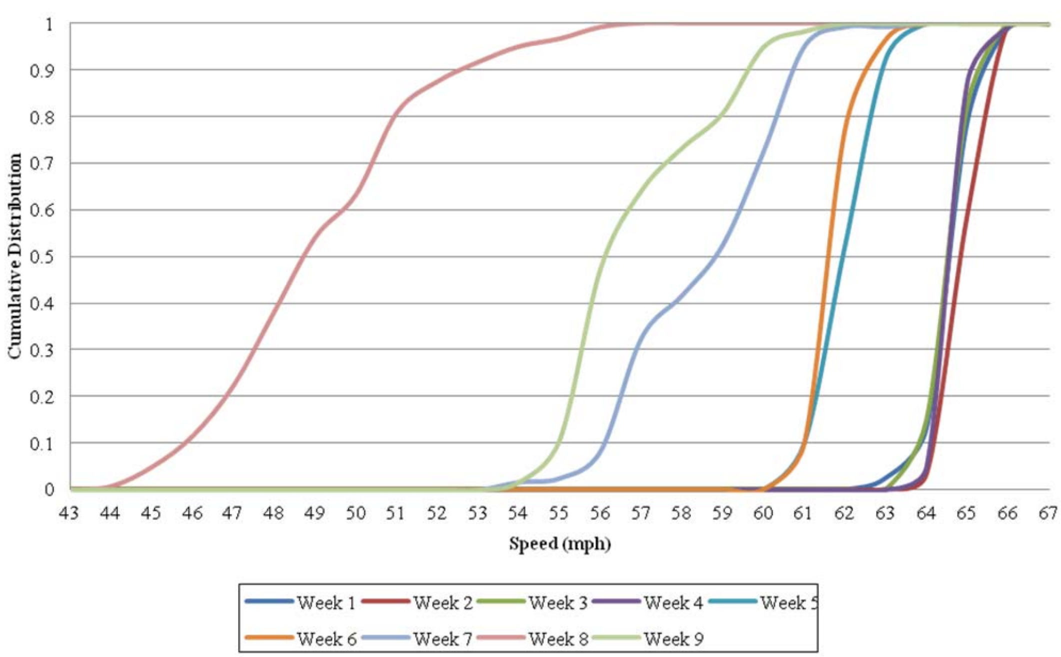


Figure 2.4.10 Cumulative speed distribution for 9 weeks of enforcement on I-64 during the afternoon peak hours.

2.4.2 Study Segment: I-64 (Weekends)

The traffic pattern on weekends, unlike weekdays, usually does not follow the morning and afternoon peak patterns. During weekends, uniform traffic loads and higher average speeds are expected. Figure 2.4.11 shows the weekly average speed for the I-64 segment. The figure clearly shows the drivers' tendency to drive faster during the weekends in the *before* period, as compared to the weekdays. Another important observation from this figure is the effect of enforcement on driving behavior. Enforcement was found to be more effective in reducing the average speed during the weekends.

To account for the above facts and have a better understanding of the enforcement effect on the average speed during the weekends, the whole enforcement period from 6 a.m. to 6 p.m. is considered in the analysis. Figure 2.4.12 shows the speed during the enforcement period for the first two Saturdays. This figure shows that the enforcement had a significant effect on reducing the average speed until afternoon hours (12 noon to 3 p.m.). Enforcement was less effective during the afternoon hours.

The daily and weekly average speeds during the whole enforcement period are presented in Figure 2.4.13. Table 2.4.10 shows the t-test results for the weekly average speeds during this period. The figure shows that the average speed dropped after the enforcement was initiated in the second week; however, in the third week the average speed increased again. The difference between the average speeds during the first week and the third week is not statistically significant (Table 2.4.10). This observation shows the enforcement had no effect on the average speed because of less enforcement coverage except for after 3 p.m. (see Table 4.1). Because the drivers' behavior is different during the weekends, continuous enforcement is essential to reduce the average speed.

After enforcement was resumed in the fifth week, the average speed decreased significantly in comparison with the previous weeks. Unfortunately, the enforcement covered only the segment after 3 p.m., which makes the results unreliable. By having full-time coverage, a reduction in the average speed is expected. Enforcement with less intensity in the sixth week led to an increase in the average speed. In the seventh week, the speed increased even more due to the lack of active enforcement on the segment. The P-values of the Wilcoxon rank-sum test are also presented in Table 2.4.11. On the basis of this test, almost all of the differences in the average speeds are statistically significant.

The cumulative distributions of the average speeds are presented in Figure 2.4.14. As illustrated, the average speed distributions of the second week and the ninth week have strange patterns. These results deviate from the bell-shaped distribution pattern. These observations can be related to the sudden drop in the average speed after 3 p.m. on Sundays. The results of the Kolmogorov-Smirnov test also reveal that all of the distributions are statistically different.

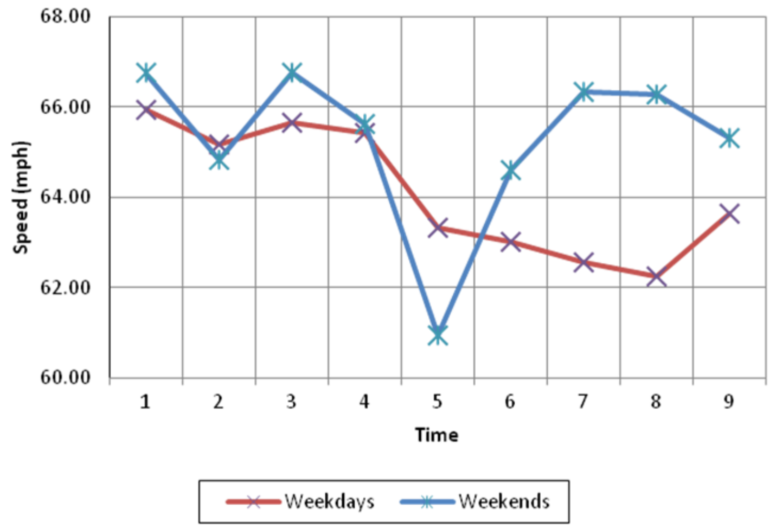


Figure 2.4.11 Comparison of the weekly average speed on weekdays and weekends on I-64 during the whole enforcement period.

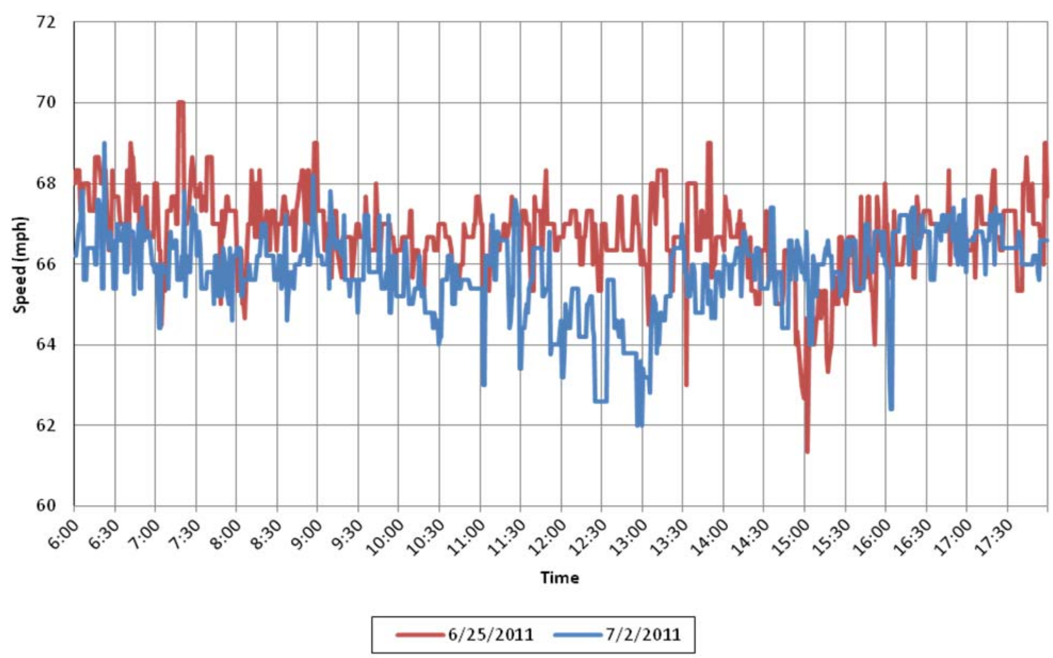


Figure 2.4.12 Average speed during the active enforcement period for the first two Saturdays.

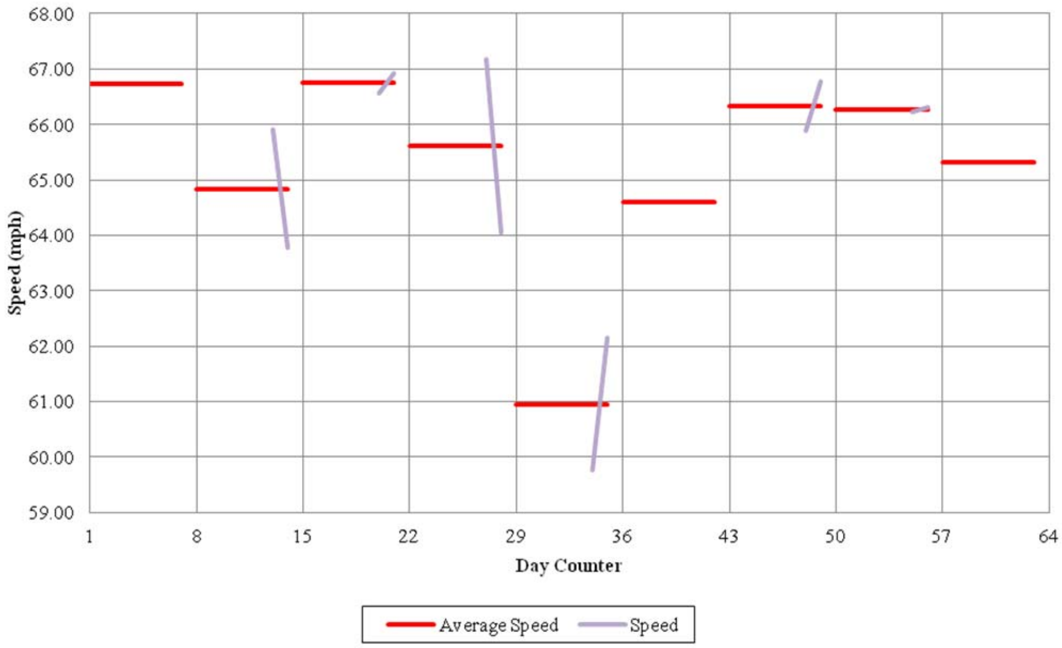


Figure 2.4.13 Daily average speed and weekly average speed during the active enforcement period for 9 weeks of enforcement on I-64.

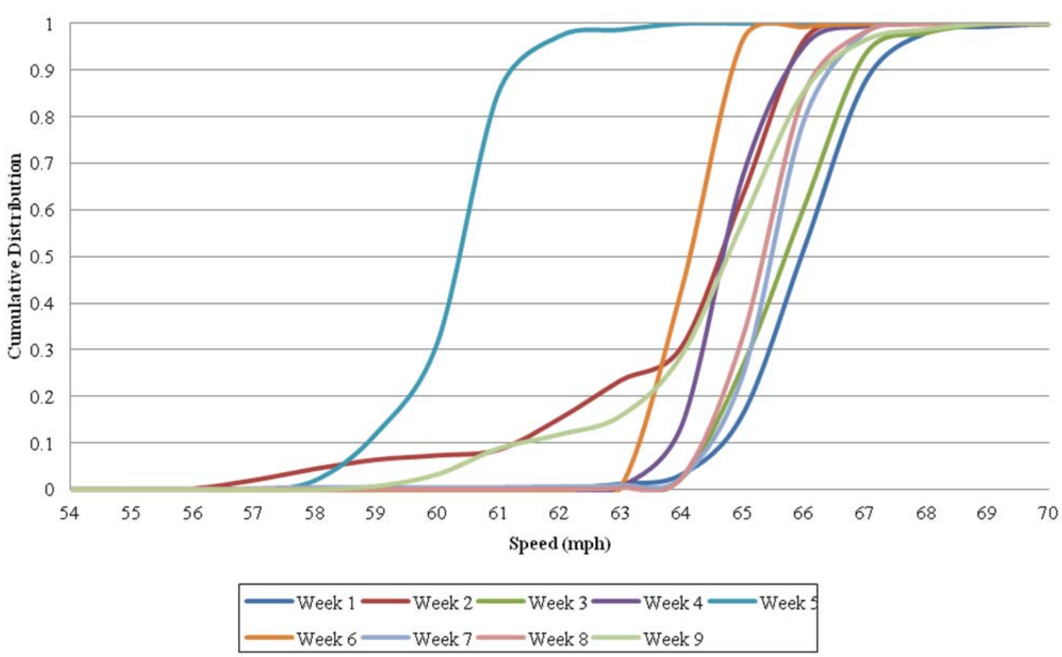


Figure 2.4.14 Cumulative speed distribution for 9 weeks of enforcement on I-64 during the whole enforcement period.

2.4.3 Study Segment: I-55/I-70 (Weekdays)

2.4.3.1 Morning Peak Period

In the calculations, the interval between 6 and 10 a.m. was considered the morning peak period. Figure 2.4.15 shows the average speed during the morning peak hours on the first three Tuesdays. Although the enforcements had an obvious effect on speed reduction, the analysis shows that its effect on variance is not considerable (the F-test result shows no meaningful difference between the variances).

The daily and weekly average speeds for the morning peak period on I-55/I-70 are presented in Figure 2.4.16, which reveals a desirable pattern in the weekly average speed during this time period. Table 2.4.12 also shows the t-test results for the weekly average speeds. The results indicate that each enforcement strategy had a statistically significant effect on the average speed.

The average speed decreased in the second week after the enforcement was initiated. A similar pattern was observed in the third week after introducing a higher-intensity enforcement strategy. Increasing the number of officers from two to four in this week resulted in a statistically significant decrease in the average speed in comparison with the second week. Because no enforcement was applied during the fourth week, the average speed increased slightly.

After the enforcement resumed in the fifth week, the average speed decreased. However, the result of the t-test shows that this reduction is not statistically significant. In the sixth week, after the last week of enforcement, a statistically significant increase in average speed occurred. However, in the last 2 weeks, the average speed did not follow the expected pattern; therefore, the study of the time halo could not be completed. It is noteworthy that the results of the Wilcoxon rank-sum test (presented in Table 2.4.13) are slightly different from the results of the t-test. The Wilcoxon rank-sum test shows that the differences in average speeds are statistically significant at the 99% confidence level, even for the cases that the t-test shows insignificant differences. The results obtained based on Wilcoxon rank-sum test are favorable because the difference in the average speed during the fourth and fifth weeks becomes statistically meaningful. In addition, if one considers the results of both tests, the data shows that the enforcement chain had statistically significant effect on reducing the average speed.

Figure 2.4.17 illustrates the cumulative speed distributions for the first 8 weeks on I-55/I-70. The figure clearly indicates that the average speed distribution shifts to the left after the start of the enforcement on this segment. Table 2.4.14 also shows the results of the Kolmogorov-Smirnov test for these distributions, which reveals the same pattern as the average speed differences. On the basis of these results, the enforcement caused statistically significant changes in the average speed distributions.

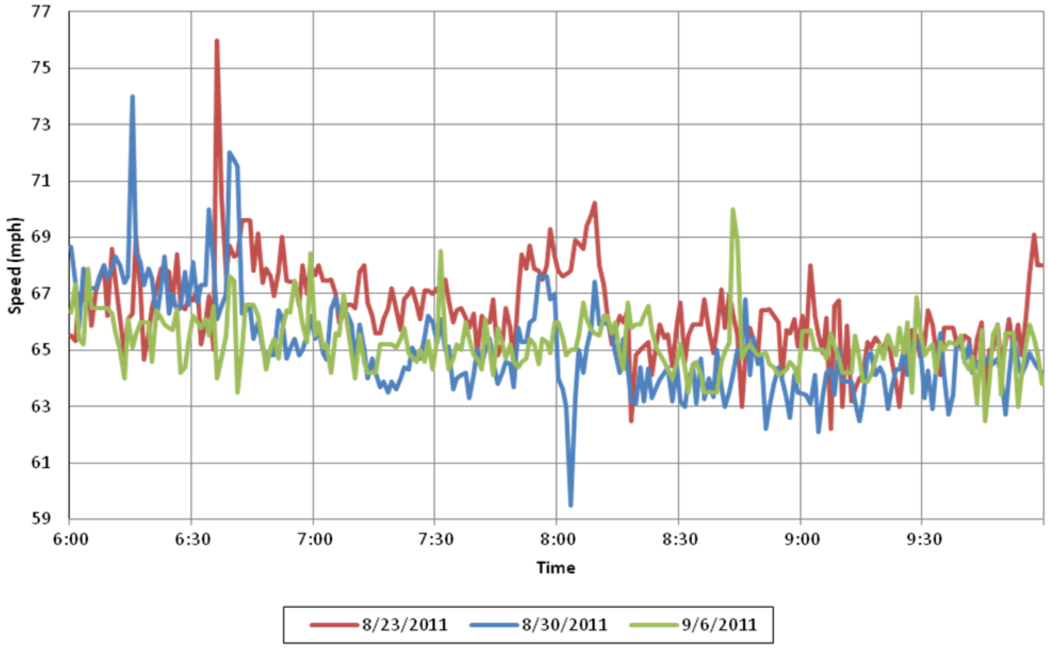


Figure 2.4.15 Average speed during the active enforcement period for the first three Tuesdays.

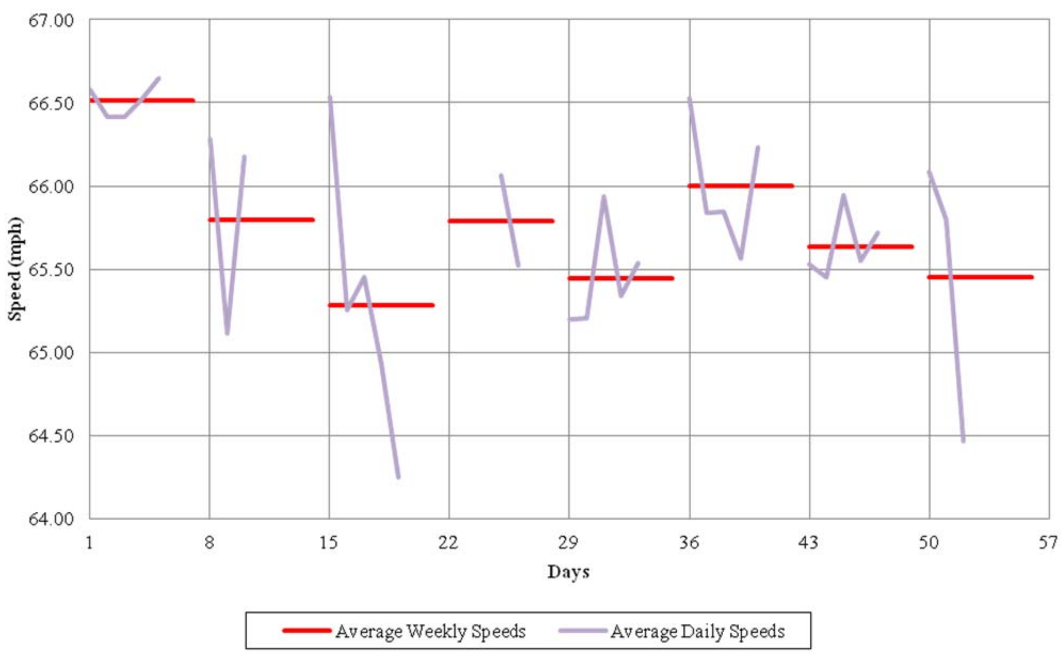


Figure 2.4.16 Daily average speed and weekly average speed during the morning peak period for 8 weeks of enforcement on I-55/I-70.

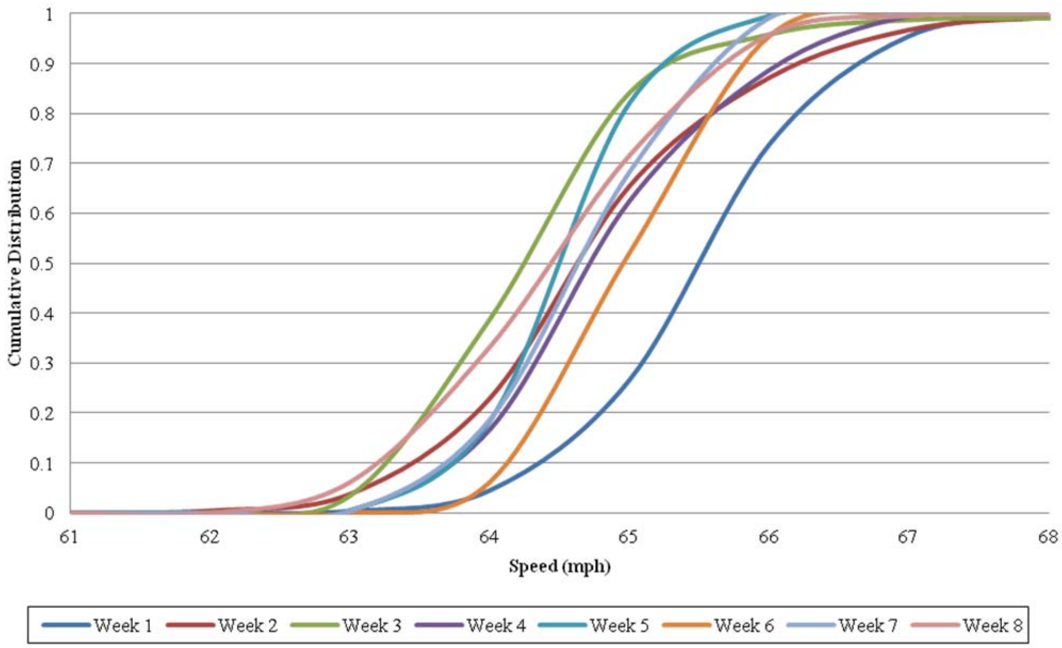


Figure 2.4.17 Cumulative speed distribution for 8 weeks of enforcement on I-55/I-70 during the morning peak period.

2.4.3.2 Nonpeak Period

The interval between 10 a.m. and 4 p.m. was considered the nonpeak period in the calculations. The daily and weekly average speeds during the nonpeak hours on I-55/I-70 are presented in Figure 2.4.18. The t-test results for this data are also presented in Table 2.4.15. The figure shows a slight reduction in the average speed because of the enforcement in the second and third weeks in comparison with the first week. However, this reduction is not statistically significant. The detectors' functionality and the active enforcement periods did not match well for the first 3 days of the fourth week. Consequently, no data are available for the first 2 days. By excluding this data from the calculations, the difference in the average speeds during the fourth week is not significantly different from that of the third and the fifth weeks. If one employs this approach, the average speed reduction is not statistically significant on any of the two consecutive weeks. However, the difference between the average speeds in the first and third weeks shows a possible effect of continuous enforcement on the average speed.

The results of the Wilcoxon rank-sum test, presented in Table 2.4.16, are very similar to the results of the t-test. The only discrepancy occurs in comparing the average speed of the first week and the second week. The Wilcoxon rank-sum test results demonstrate that this difference is statistically significant at the 99% confidence level. It should be also mentioned that by excluding the unreliable data from the analysis, the differences in the average speeds between the third week, the fourth week, and the fifth week are not statistically significant.

Figure 2.4.19 presents the cumulative speed distributions for the first 8 weeks on I-55/I-70. The results of the Kolmogorov-Smirnov test are presented in Table 2.4.17. Unlike the two previous tests, the Kolmogorov-Smirnov test shows significant differences in the average speed distributions due to the enforcement. All of the distributions are statistically different at the 95% confidence level, except the distributions in the second and fifth weeks. However, the enforcement expanded the speed distributions for this period, which is a negative rather than a positive effect. In sum, the enforcement on this segment had a very small positive effect on reducing the average speed and had a negative effect on the average speed distributions.

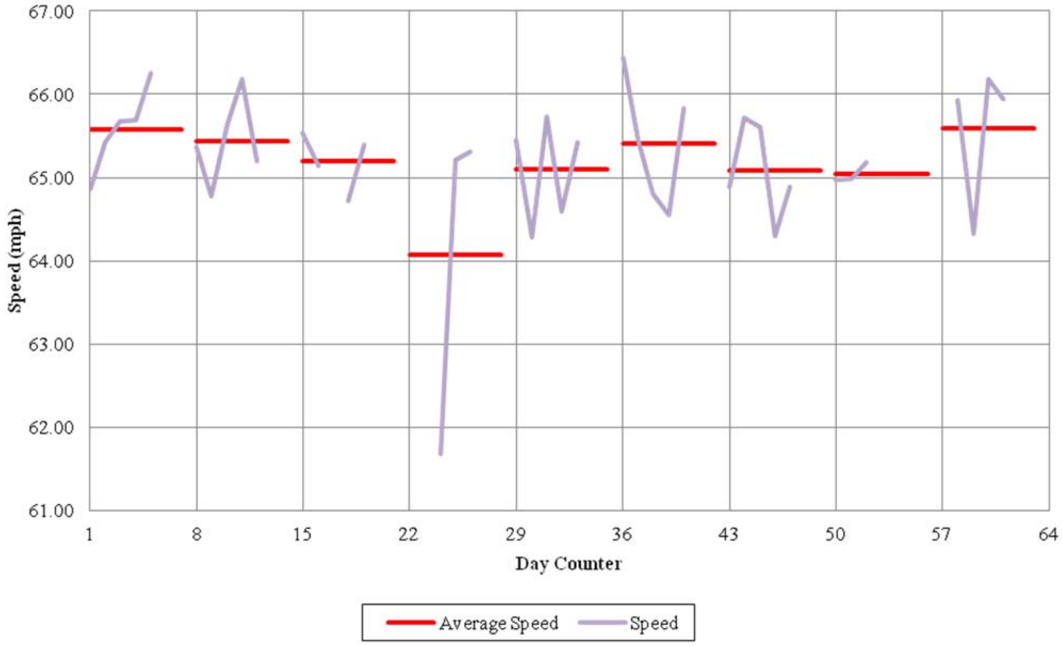


Figure 2.4.18 Daily average speed and weekly average speed during the nonpeak period for 8 weeks of enforcement on I-55/I-70.

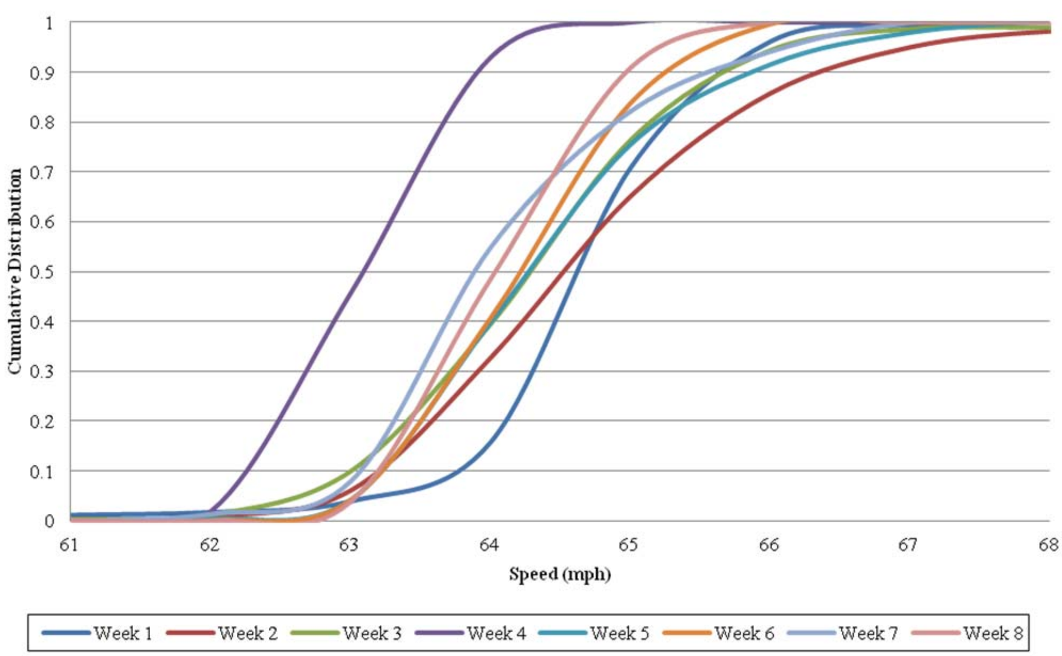


Figure 2.4.19 Cumulative speed distribution for 8 weeks of enforcement on I-55/I-70 during the nonpeak period.

2.4.3.3 Afternoon Peak Period

The interval between 4 and 6 p.m. was considered the afternoon peak period in the calculations. Figure 2.4.20 shows the daily and weekly average speeds during the afternoon peak period on this segment, and Table 2.4.18 presents the t-test results for this data. A comparison between the average speed during the first and second weeks reveals that the enforcement had a statistically significant effect in reducing the average speed.

The detectors' functionality and active enforcement periods did not match well during the third, fourth, and fifth weeks. As a result, no or very limited data was obtained during these weeks. Thus, no reliable conclusion can be made on the effect of enforcement. The average speed during the sixth week was higher than during the second week, which can be interpreted as an increase in the average speed after the last week of enforcement. The length of the time halo can be determined as 1 week because the difference between the average speeds of the first and seventh weeks is not statistically significant.

The results of the Wilcoxon rank-sum test (Table 2.4.19) also reveal the same pattern as the t-test. Figure 2.4.21 presents the cumulative speed distributions for the first 8 weeks on I-55/I-70. In addition, Table 2.4.20 shows the results of the Kolmogorov-Smirnov test for these distributions. On the basis of the test results, the difference in the speed distributions between the first and the second weeks is statistically significant. However, this difference is not statistically significant for the first and seventh weeks. Figure 2.4.21 also indicates the similarity of the speed distributions during the first and seventh weeks.

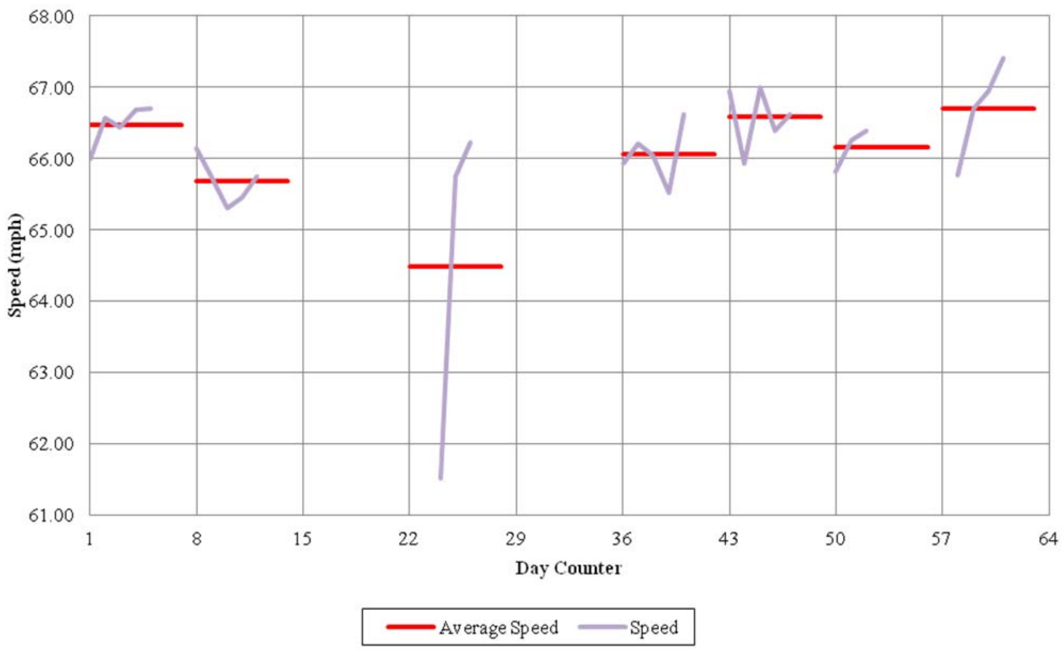


Figure 2.4. 20 Daily average speed and weekly average speed during the afternoon peak period for 8 weeks of enforcement on I-55/I-70.

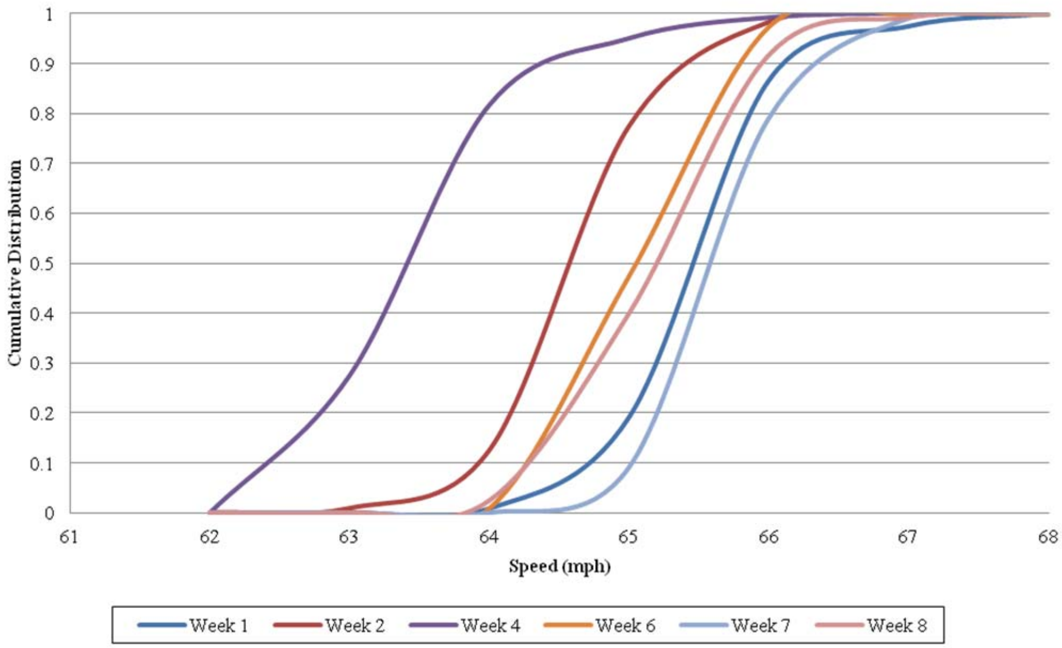


Figure 2.4.21 Cumulative speed distribution for 8 weeks of enforcement on I-55/I-70 during the afternoon peak period.

2.4.4 Study Segment: I-55/I-70 (Weekends)

It was explained in Section 2.4.2 that the traffic pattern on weekends differs from the traffic pattern on weekdays. On weekends, the traffic load on the highway is nearly uniform loading throughout the day, with a lower flow rate than on a typical weekday. Figure 2.4.22 shows the weekly average speeds during the 8 weeks of enforcement for both weekdays and weekends. The figure clearly shows that there was a tendency toward higher speeds during weekends, which happened mainly because of the low flow rate during the weekends, which gave drivers the freedom to maneuver. This tendency was even higher on I-55/I-70 in comparison with I-64. Assuming that drivers tend to drive at the same speed (close to the speed limit) during the weekdays and weekends in the presence of the patrolling units, more reduction could be observed during the weekends, as drivers tend to driver at higher speeds. Thus, similar to the data on I-64, the enforcement was more effective during the weekends (compare the reduction in average speed in the first and second weeks).

Figure 2.4.23 shows the daily and weekly average speeds for the whole enforcement period during the weekends. The figure shows an undesirable pattern throughout the whole period. The data in the second and third weeks are very unreliable. No data are available for Sunday, as well as for some part of Saturday, during the third week (the enforcement covered fewer than 6 of 12 hours on Saturday). A very discontinuous enforcement on the fifth Sunday led to a higher average speed, in comparison with the previous week, which had no enforcement.

Table 2.4.21 shows the t-test results, and Table 2.4.22 presents the P-values of the Wilcoxon rank-sum test. The results show that almost all the differences in average speeds are statistically significant. The only conclusion is the positive effect of enforcement on the speed reduction; however, the amount of this influence cannot be determined because of the lack of accurate data.

Figure 2.4.24 shows the cumulative speed distributions. In this figure, the differences between the distributions are clear, and they are confirmed by the Kolmogorov-Smirnov test results (Table 2.4.23).

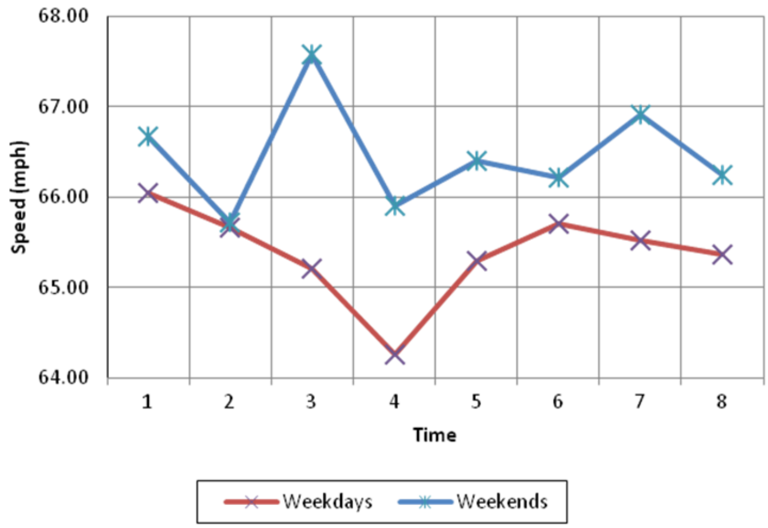


Figure 2.4.22 Comparison of weekly average speed on weekdays and weekends on I-55/I-70 during the whole enforcement period.

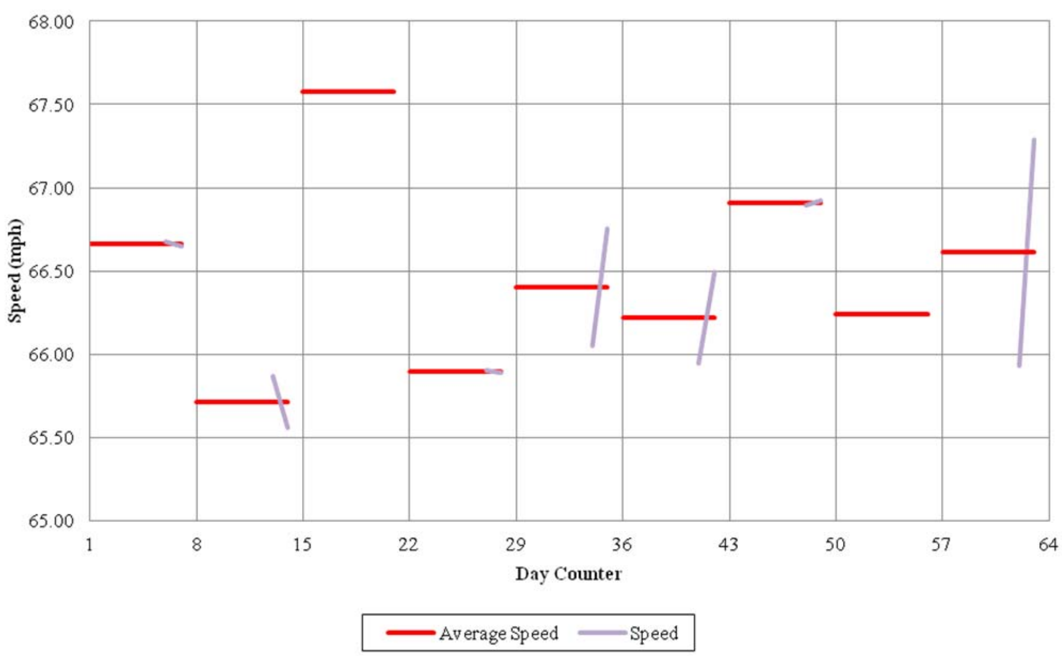


Figure 2.4.23 Daily average speed and weekly average speed during the active enforcement period for 8 weeks of enforcement on I-55/I-70.

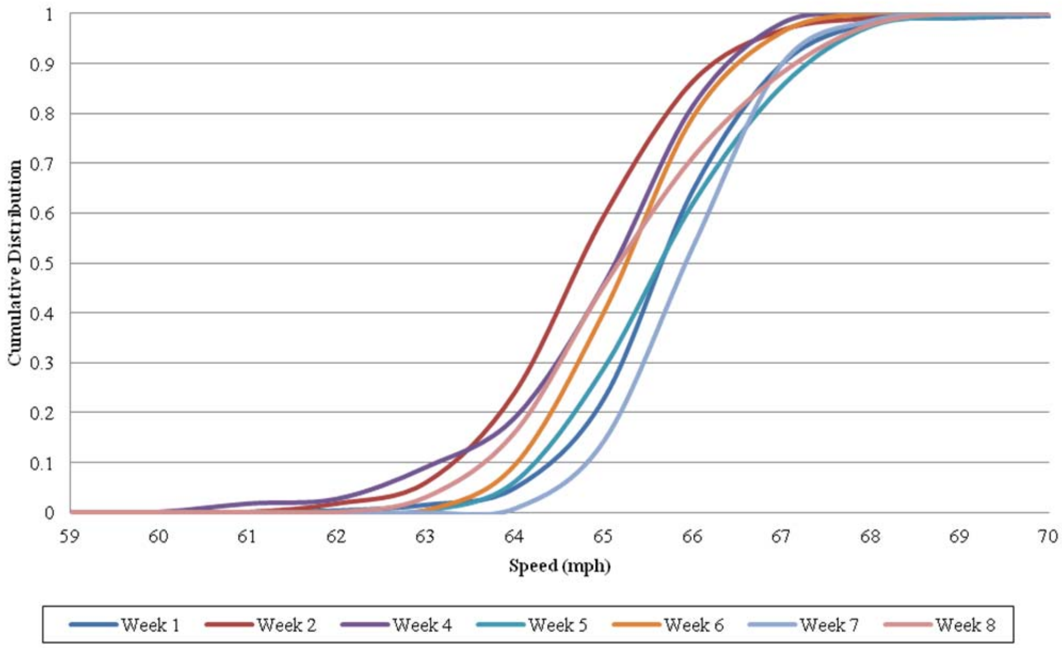


Figure 2.4.24 Cumulative speed distribution for 8 weeks
of enforcement on I-55/I-70 during the active enforcement period.

2.4.5 Analysis of the Time Halo

The effects of speed enforcement are limited in time and space. The term “halo” in speed enforcement refers to the time until the effects of enforcement on the drivers’ speed completely disappear (time halo) or it refers to the distance from the active enforcement location at which the effects of enforcement on the drivers’ speed completely disappear (space halo) (SafetyNet 2009). Existence of the halo effect (in both time and space), its duration, and its spatial extent highly depend on the characteristics of the enforcement location, the enforcement method, and its intensity.

The analysis of the space halo is not possible in this study due to the limited availability of detectors in and around the study area, as well as the prevailing congested conditions as drivers approach the downtown St. Louis using I-64 and I-55. Thus, the study of the time halo is the main interest in this study. Figure 2.4.25 shows the weekly average speed during the study period. In this figure, the start of the enforcement on each segment is marked as week 1. It reveals a time halo of 5 weeks on I-55/I-70. Also, the difference between the average speed in the first week and tenth week is not statistically significant at the 99% confidence level, based on the t-test. However, one could consider the time halo of 2 weeks on this segment as a practical approximation because the average speeds during the first and seventh weeks were very close to each other.

The average speed on I-64 at the end of the ninth week was about 2 mph below the *before* period. This large difference is due to the very low average speed during the afternoon peak period during that week (around 50 mph). Also the average speed on I-64 could be influenced by enforcement on the other segment after the ninth week. These facts make the time halo studies unreliable on this segment.

However, by considering just the morning peak and nonpeak periods in the analysis, along with the large effect of the stationary overt method on reducing the average speed (see Section 2.4.4), a time halo length similar to that on I-55/I-70 is expected on this segment. Therefore, a time halo of at least 2 weeks was identified for this study.

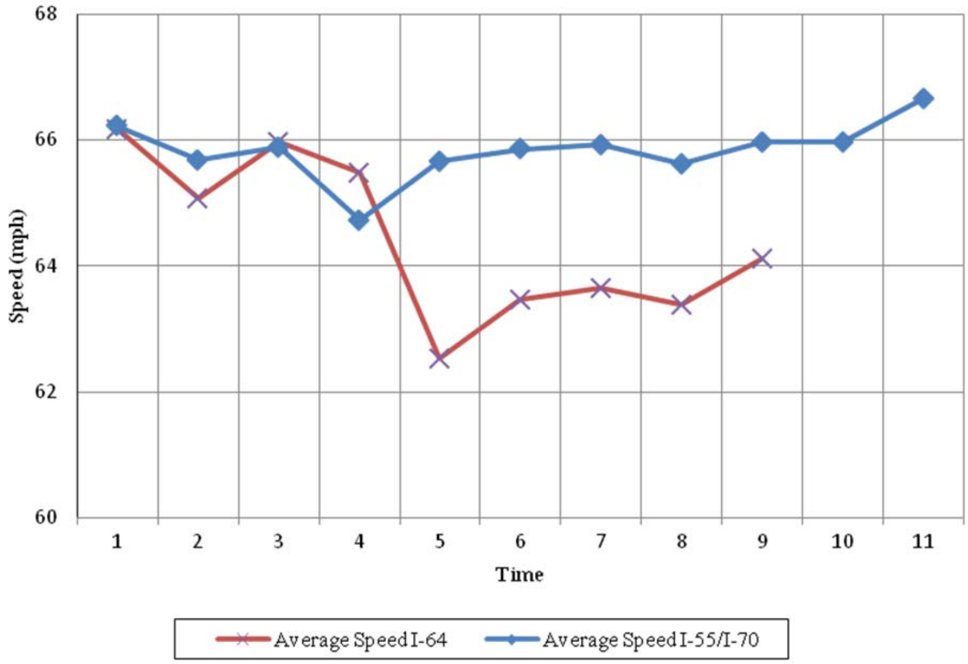


Figure 2.4.25 Weekly average speed on I-64 and I-55/I-70 during the study period.

2.4.6 Analysis of Crash Rate

The main objective of any speed-enforcement program is to improve safety. Even though the average speed and the number of citations issued are the two accurate indicators of this improvement, the crash rate itself is also a direct indicator for it. Unfortunately, the duration of the study was not long enough for accurately analyzing the effect of the enforcement on crash rates. However, a simple exploratory analysis of crash rates can be performed; it is discussed in this section.

Table 2.4.24 shows daily crash rates on I-64 since 2004. The crash rates are calculated based on the average daily crash rate during June, July, and August on this segment. It is noteworthy that, for 2011, the crash rate is calculated based on the crash information from the weeks under the influence of the enforcement (4 weeks of active enforcement and 1 week in between).

Table 2.4.25 also shows the daily crash rates on I-55/I-70 since 2004. The crash rates are calculated based on the average daily crash rate during August, September, and October on this segment. Similar to that of the I-64 segment, the crash rate is calculated based on the crash information from the weeks under the influence of the enforcement (3 weeks of active enforcement and 1 week in between).

The two tables clearly show that the total and property-damage average crash rates were reduced during the enforcement. For instance, the total average crash rate was reduced by more than half from 2006 through 2011 on I-64. However, for the fatal crashes, the average crash rates remained constant on I-64 and increased on I-55/I-70. A similar pattern in the average crash rates was observed for the B-injury crashes. Unfortunately, it is difficult to investigate the reasons behind these observations because of the limited data; however, the available data suggest that the enforcement had a positive impact in reducing the average crash rates and improving safety.

CHAPTER 3 STATEWIDE STUDY

The pilot study, described in the preceding chapter, provided information to study the effects of different enforcement strategies and intensities on driver compliance and the resulting driving speed. The present chapter describes the statewide extension of the study to consider various geographic locations across the state. The process for recommending the additional locations, which used information from the pilot study, is described. The chapter follows a similar structure as the previous one. After describing the study locations in the first section, the enforcement strategies tested and protocols followed are detailed in Section 3.2. Next, the analysis methodology is presented in Section 3.3, followed by the results from the statewide tests, along with the principal technical findings.

3.1 DATA COLLECTION AND INITIAL PROCESSING

Four highway segments were selected in Illinois, and different combinations of enforcement strategies and intensities were planned for each segment. In the following sections, the study locations and their characteristics are introduced; and then the selected enforcement plans for each segment are discussed in detail.

3.1.1 Statewide Study Locations

This section provides basic information about selected study locations in Illinois. The same criteria as in the pilot study were considered in choosing the statewide study locations, namely

- Crash rate
- Length of the segments
- Avoiding construction zones
- Availability of occupancy loop detectors and speed detectors
- Ability to perform both overt and covert enforcement
- Existence of a control section similar in characteristics to the study sections

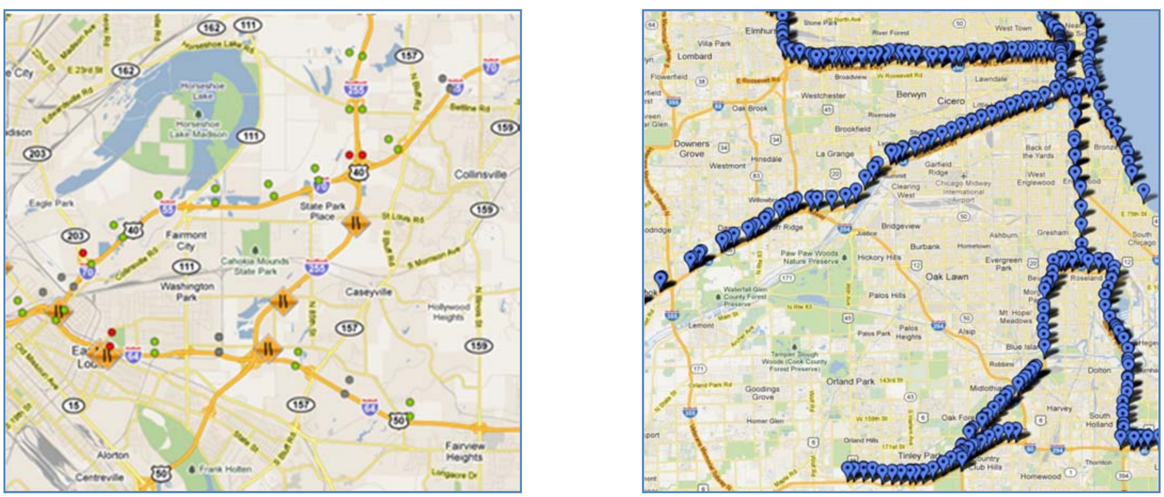
Five crash types (fatal injury, A-injury, B-injury, C-injury, and property damage) were considered for the site selection. IDOT WebCubeBrowser and IDOT GIS dataset are the two crash-data sources used for site selection. The GIS dataset covers Illinois from 2001 through 2009. By contrast, the WebCubeBrowser covers crashes throughout Illinois from 2005 through 2010 (it has information on fatal crashes for 2004 as well). Besides the crash rate, the segment length was also considered. A very short segment could reduce the accuracy of the study, while a very long segment would increase the cost. Considering these factors, availability of 5- to 10-mi segments, along with places to hide the police vehicles, was taken into account in the site selection. In addition, the existence of occupancy loop detectors and speed-detection sites was also considered.

Figure 3.1.1 shows the location of the loop detectors in the selected study areas. The Illinois Department of Transportation (IDOT) database and St. Louis Metropolitan Area Traveler Information website (http://www.stl-traffic.org/Default.aspx) were used to confirm the loop detector locations; and IDOT GIS data was used to locate the speed-detection sites. As previously noted, construction zones were avoided in this study.

On the basis of the above criteria, four highway segments were selected for the statewide study. In the following sections, these highway segments and their characteristics are discussed in detail.

3.1.1.1 Segment 1: I-55

This segment is located in Cook County near Chicago, between the IL-50 and the IL-45 highways, with a length of 7.8 mi (Figure 3.1.2). It has three lanes in each direction with two left and one right curves in the eastbound direction; it also has three overpasses. There are 30 detection sites with occupancy loop detectors on this highway segment (15 in each direction), and no speed-detection site is located on this highway. Figure 3.1.3 shows the various types of crashes on this road segment, based on the IDOT WebCubeBrowser data from 2004 through 2010. The segment had 34.89 crashes per mile per year and 1.19 crashes per million vehicle miles traveled (based on the IDOT crash data from 2004 through 2009). The I-290 highway is considered as the control segment for this study because the two segments are similar, and they serve different parts of the region. It is also expected that the start of enforcement on I-55 would not affect the traffic on I-290. Interstate 290 should provide a reliable control segment for the purpose of a before-and-after study. Note that the loop detector coverage on this highway extends beyond the limits of the selected segment in both the east and west directions, providing an excellent opportunity to investigate the existence of space halo.



(a) (b)

Figure 3.1.1 Loop detector coverage at the study locations:
(a) East St. Louis area (Source: St. Louis Metropolitan Area Traveler Information website);
(b) Chicago area (Source: Illinois Department of Transportation).

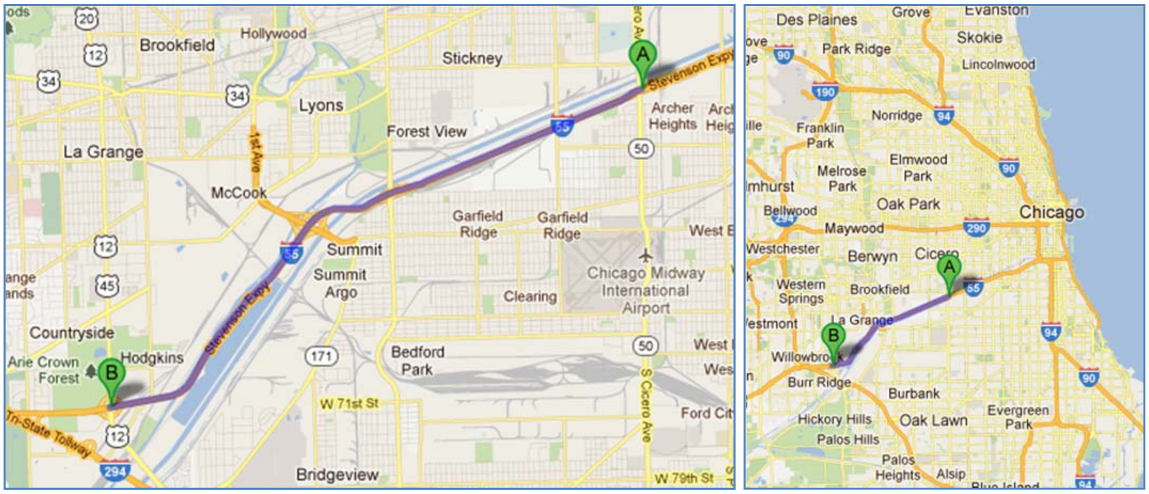
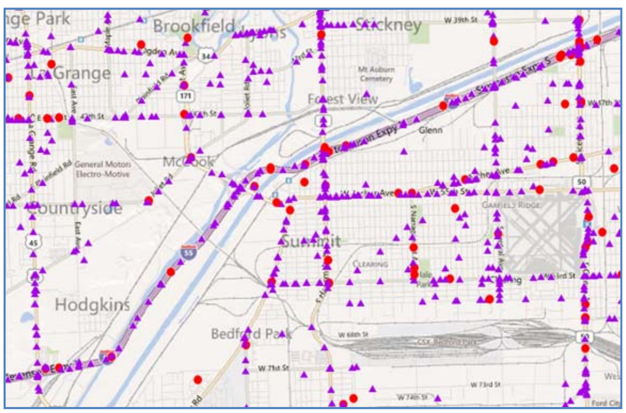
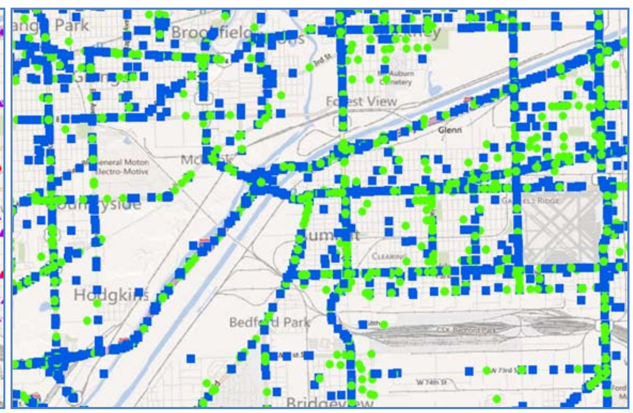


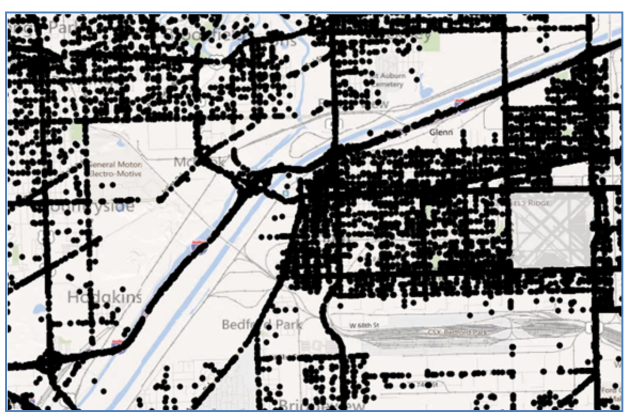
Figure 3.1.2 Study segment on I-55.



(a) Fatal and A-injury: red circles show fatal crashes, and purple triangles show A-injury crashes



(b) B-injury and C-injury: blue rectangles show B-injury crashes, and green circles show C-injury crashes



(c) Property damage

Figure 3.1.3 Various crash types for the segment on I-55. (Source: IDOT CubeWebBrowser)

3.1.1.2 Segment 2: I-57

This segment is located in Cook County near Chicago, between West 111th Street and West 147th Street (IL-83), with a length of 5.1 mi (Figure 3.1.4). It has three lanes in each direction with two left and two right curves in the eastbound direction; it also has five overpasses. There are 26 detection sites with occupancy loop detectors on this highway segment (13 in each direction), and no speed-detection site is located on this highway. Figure 3.1.5 shows the different types of crashes on this road segment, based on the IDOT WebCubeBrowser data from 2004 through 2010. The segment had 15.31 crashes per mile per year and 0.63 crashes per million vehicle miles traveled (based on the IDOT crash data from 2004 through 2009). The I-290 highway is considered the control segment for this site because the two segments are similar, yet they serve different parts of the region. It is also expected that the start of the enforcement on I-57 would not affect the traffic on I-290. I-290 should provide a reliable control segment for the purpose of a before-and-after study. Note that the loop detector coverage on the south side of the segment, unlike the north side, is limited, which imposes some limitation on the ability to investigate space halo.

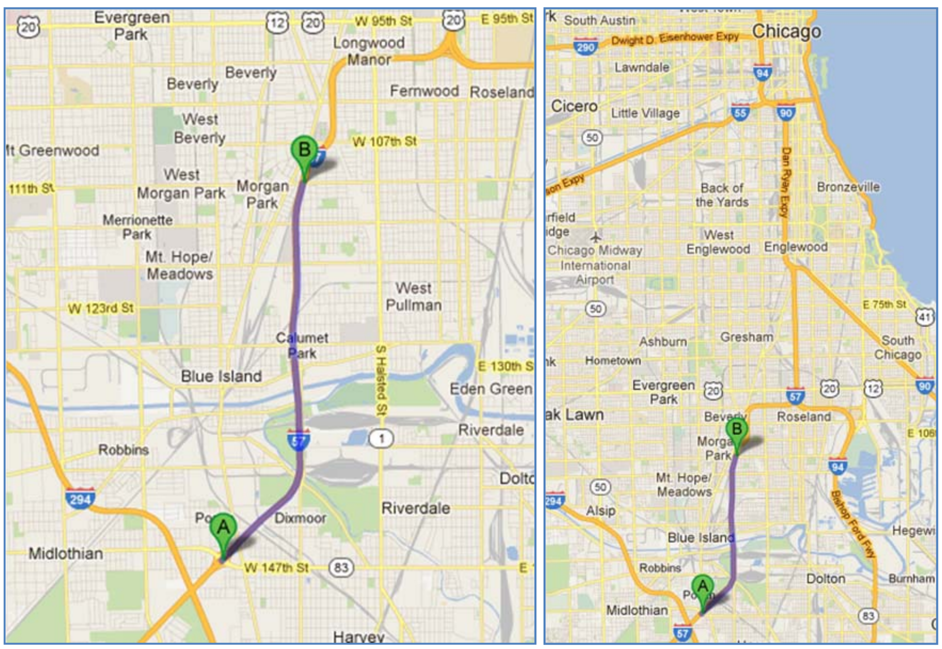
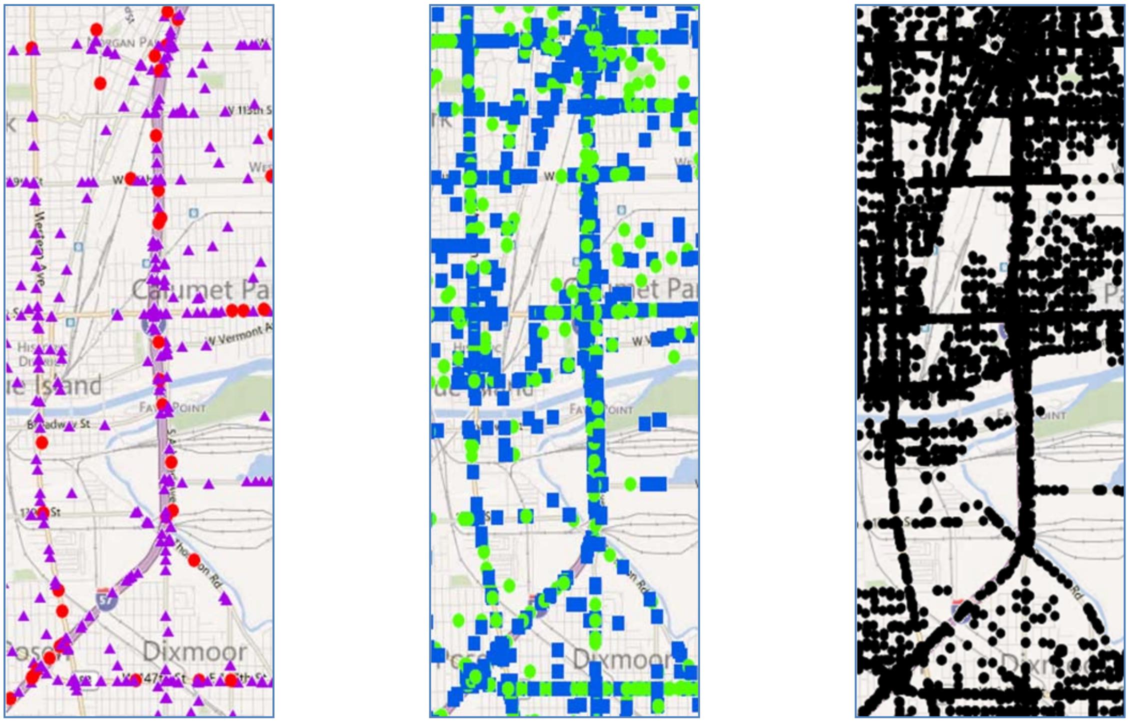


Figure 3.1.4 Study segment on I-57.



(a) Fatal and A-injury: red circles show fatal crashes, and purple triangles show A-injury crashes

(b) B-injury and C-injury: blue rectangles show B-injury crashes, and green circles show C-injury crashes

(c) Property damage

Figure 3.1.5 Various crash types for the segment on I-57. (Source: IDOT CubeWebBrowser)

3.1.1.3 Segment 3: I-94

This segment is located in Cook County near Chicago, between East 111th Street and 159th Street, with a length of 6.7 mi (Figure 3.1.6). It has three lanes in each direction with three left and four right curves in the eastbound direction; it also has seven overpasses. There are 32 detection sites with occupancy loop detectors on this highway segment (16 in each direction), and no speed-detection site is located along this highway. Figure 3.1.7 shows the various types of crashes on this road segment, based on the IDOT WebCubeBrowser data from 2004 through 2010. The segment had 36.99 crashes per mile per year and 1.33 crashes per million vehicle miles traveled (based on the IDOT crash data from 2004 through 2009). The I-290 highway is considered a control segment for this study because the two segments are similar, yet they serve different parts of the region. It is also expected that the start of the enforcement on I-94 would not affect the traffic on I-290. I-290 should provide a reliable control segment for the purpose of a before-and-after study. Note that, similar to that of the I-57 segment considered, the loop detector coverage on the south side of the segment is limited, thereby limiting the ability to ascertain existence of space halo.

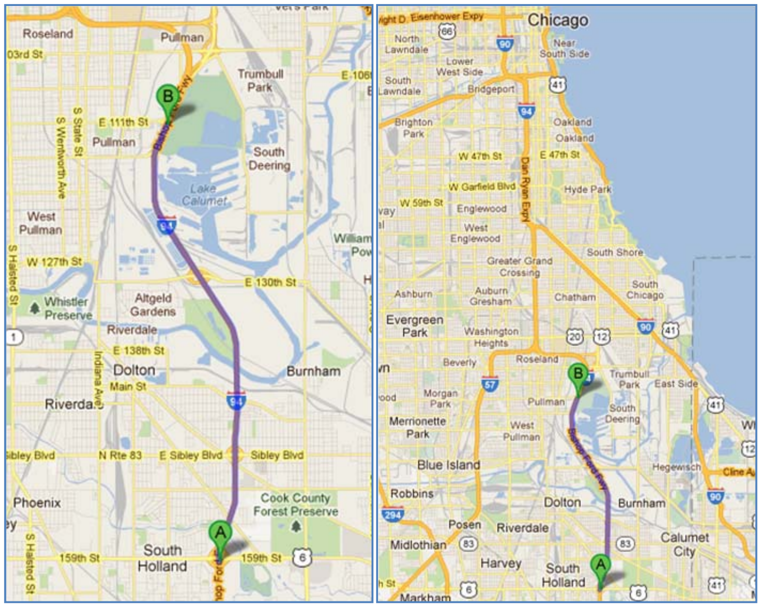
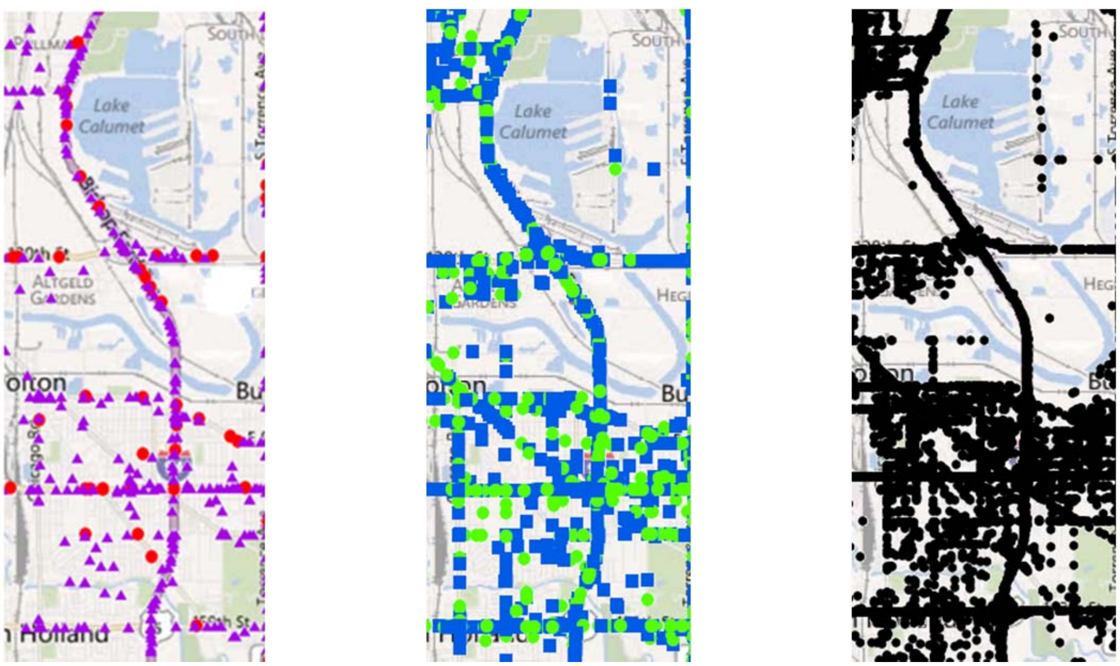


Figure 3.1.6 Study segment on I-94.



(a) Fatal and A-injury: red circles show fatal crashes, and purple triangles show A-injury crashes

(b) B-injury and C-injury: blue rectangles show B-injury crashes, and green circles show C-injury crashes

(c) Property damage

Figure 3.1.7 Various crash types for the segment on I-94. (Source: IDOT CubeWebBrowser)

3.1.1.4 Segment 4: I-55/I-70

This segment is located in St. Clair County near East St. Louis, between IL 203 and North Bluff Road (IL 157), with a length of 6.8 mi (Figure 3.1.8). It has three lanes in each direction with two left and one right curves in the eastbound direction; it also has four overpasses. There are 14 detection sites with occupancy loop detectors on this highway segment (7 on each direction), and no speed-detection site is located on this highway. Figure 3.1.9 shows the different types of crashes on this road segment, based on the IDOT WebCubeBrowser data from 2004 through 2010. The segment had 6.21 crashes per mile per year and 0.69 crashes per million vehicle miles traveled (based on the IDOT crash data from 2004 through 2009). Although the I-270 highway is the best choice for a control segment (because of the similarity to I-55/I-70), the unavailability of flow data, and the existence of active work zones in the segment make it impossible to track the changes in the drivers' behavior during the enforcement period in this area. Note that the loop detector coverage on both sides of the segment is limited, thereby limiting the ability to ascertain the existence of space halo.

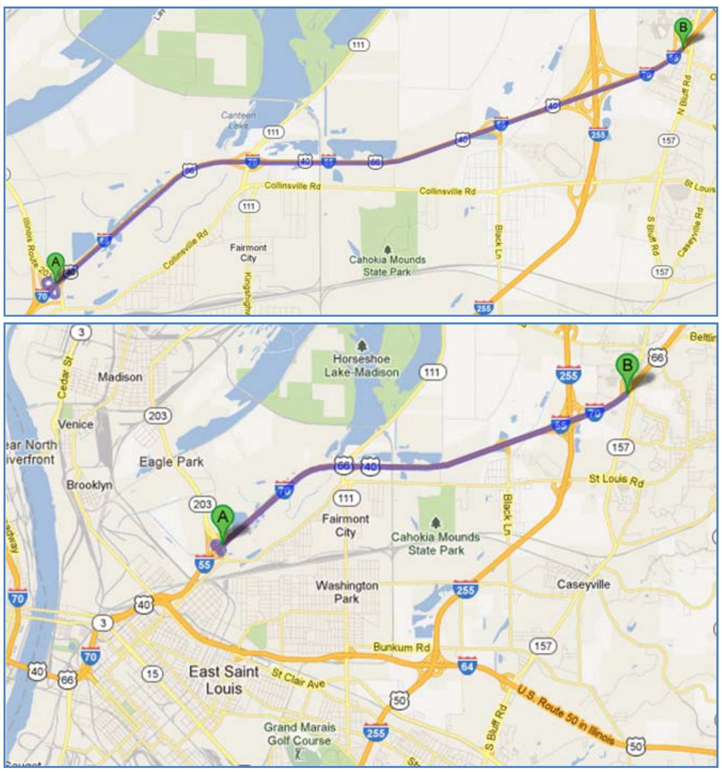
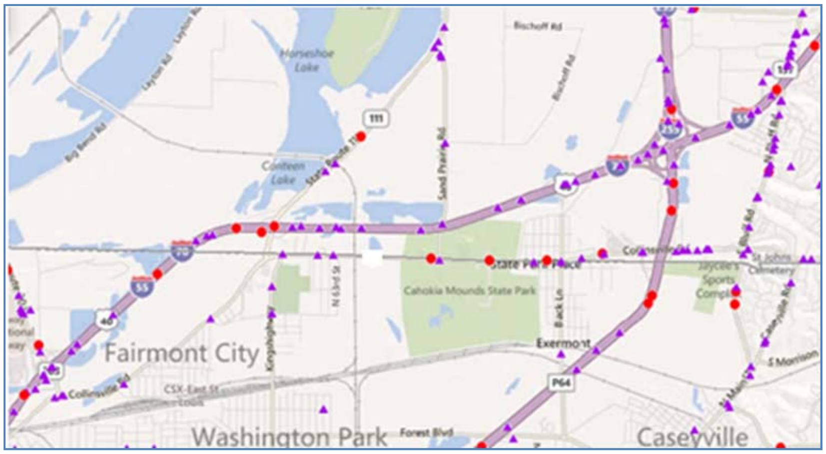
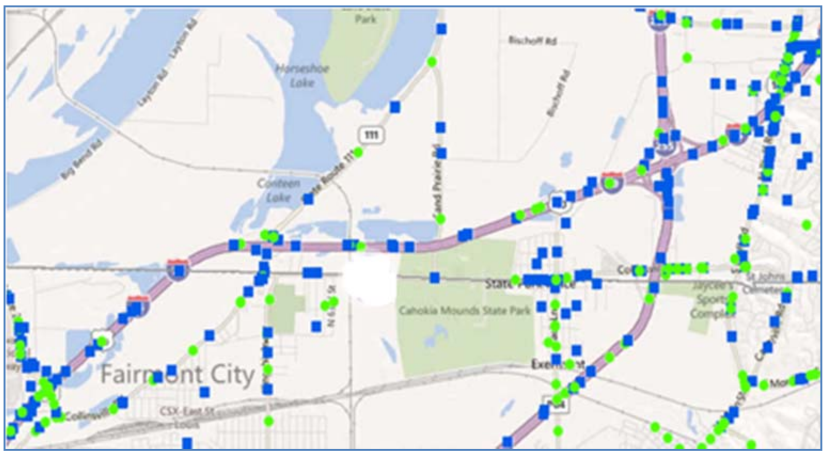


Figure 3.1.8 Study segment on I-55/I-70.



(a) Fatal and A-injury: red circles show fatal crashes,
and purple triangles show A-injury crashes



(b) B-injury and C-injury: blue rectangles show B-injury crashes,
and green circles show C-injury crashes

(c) Property damage

Figure 3.1.9 Various crash types for the segment on I-55/I-70.
(Source: IDOT CubeWebBrowser)

3.2 ENFORCEMENT STRATEGIES/STUDY DESIGN

The statewide study was designed to achieve the following goals:

- Study the effectiveness of various types of enforcement
- Investigate the existence of halo effect
- Identify better resource-allocation strategies

In the following sections, the selected enforcement strategies on each highway segment are introduced. A brief description of the resulting dataset is also provided.

3.2.1 Statewide Study Enforcement Strategies

This section introduces the selected enforcement strategies for the statewide study. On the basis of the findings of the pilot study and the previous meeting with the Illinois State Police (ISP) to identify the customary patrolling methods, certain enforcement strategies with various intensities were selected. The objective was to analyze the effects of enforcement on the average speed, crash rate, speed distribution, and speed limit compliance. The study design focused mainly on comparing various enforcement strategies in terms of safety measures and investigating the existence of time and space halo. The enforcement was planned for the morning peak period (6 to 11 a.m.) and the afternoon peak period (3 to 7 p.m.). Table 3.2.1 shows the selected patrolling strategies on each study segment. These strategies were chosen based on the following objectives:

- Identify the most effective patrolling strategies: Three common patrolling strategies (stationary overt, stationary covert and circulating) with a platoon size of two officers were selected on I-55/I-70 to capture the effects of each strategy on the average speed and crash rate.
- Identify the effect of various resource-allocation strategies: On the basis of the findings of the pilot study, three combinations of the stationary overt strategy with one, two, and four officers were selected to study the effects of each combination on the average speed, speed distribution, and crash rate. The enforcement plan on I-55 started with the highest intensity (four officers) and tapered to the lowest intensity (one officer). The enforcement plan on I-94 was uniform in terms of intensity (two officers patrolling during the active enforcement periods). The enforcement plan on I-57 started with the lowest intensity (one officer) and ramped up to the highest intensity (four officers).
- Investigate the existence and characteristics of the time halo: Seven weeks of no enforcement were monitored after the last week of active enforcement to study the time halo. These seven weeks were monitored for each enforcement combination on I-55, I-57, and I-94. The existence of time halo was investigated using the average speed from the loop detectors along these highways.

As in the pilot study, a form was designed to collect the information regarding the patrolling location, patrolling hours, number of issued citations, weather conditions, and patrolling vehicle. This form is presented in Figure 3.2.1

ICT-R27-66 Effectiveness of Innovative Speed Enforcement Techniques in Illinois

Daily Patrol Result

Illinois Department of Transportation | Illinois State Police | Northwestern University

Officer ID ____________________ Date: / / 2012

Location: I-55 ☐ I-57 ☐ I-94 ☐ I-55/I-70 ☐

Start Time: ------ : ------ (am/pm)

End Time: ------ : ------ (am/pm)

Number of Speeding Tickets: ____

Number of Speeding Warnings: ____

Number of Accidetns / Types: ____________________

Type of Strategy: ☐ Circulating Overt ☐ Stationary Overt ☐ Stationary Covert

Weather: ☐ Clear ☐ Rainy ☐ Heavy Rain

Patrolling Vehicle: Car ☐ Motorcycle ☐

Hourly Report:

(Check each box if you patrol at the corresponding period)

6:00 - 7:00	7:00 - 8:00	8:00 - 9:00	9:00 - 10:00	10:00 - 11:00		15:00 - 16:00	16:00 - 17:00	17:00 - 18:00	18:00 - 19:00

Figure 3.2.1 Daily patrol result form.

3.2.2 Brief Description of the Datasets

Dataset 1 was collected from the occupancy loop detectors on I-55/I-70 in East St. Louis. The locations of the detectors are presented in Figure 3.1.1. The speed data are available in 1-minute intervals for this segment. Unfortunately, flow and occupancy data are not available for this segment. The collected data are aggregated into 5-minute intervals to facilitate comparison of the results with the other datasets. The planned enforcement on this segment covered the periods of 6 to 11 a.m. and 3 to 7 p.m. The enforcement on this segment started on July 16, 2012, after 2 weeks of no enforcement. The last day of the enforcement on this segment was September 22, 2012. After this date, 2 weeks of no enforcement followed.

Dataset 2 was collected from the occupancy loop detectors on I-55 in Chicago. The locations of the detectors were also presented in Figure 3.1.1. The speed data are available in 5-minute intervals. The enforcement on this segment took place between 5 a.m. and 1 p.m. The enforcement on this segment started on July 16, 2012, after 2 weeks of no enforcement. The last day of enforcement on this segment was August 14, 2012. After this date, 7 weeks of no enforcement followed.

Dataset 3 was collected from the occupancy loop detectors on I-57 in Chicago. The location of the detectors was also presented in Figure 3.1.1. The speed data are available in 5-minute intervals. The enforcement on this segment took place between 5 a.m. and 1 p.m. The enforcement on this segment started on July 16, 2012, after 2 weeks of no enforcement. The last day of enforcement on this segment was August 16, 2012. After this date, 7 weeks of no enforcement followed.

Dataset 4 was collected from the occupancy loop detectors on I-94 in Chicago. The locations of the detectors were also presented in Figure 3.1.1. The speed data are available in 5-minute intervals. The enforcement on this segment took place between 5 a.m. and 1 p.m. The enforcement on this segment started on July 18, 2012, after 2 weeks of no enforcement. The last day of enforcement on this segment was August 14, 2012. After this date, 7 weeks of no enforcement followed.

3.3 METHODOLOGY

The effectiveness of each enforcement strategy was evaluated from the following standpoints: average speed and number of citations.

The average speed for each treatment was calculated based on 5-minute average speed data obtained from the loop detectors for the study segments (Figure 3.1.1). The average speed for every 5 minutes of active enforcement was calculated using data from the operational loop detectors. The averaging approach was selected because of the unknown location of patrolling unit(s) along the study segments. A volume-weighted average was calculated when volume data were available; otherwise, the arithmetic mean was calculated.

It is important to note that the actual enforcement did not exactly follow the planned enforcement schedule. Limited availability of troopers, crashes, maximum working hour restrictions (for the troopers), arrests, and other unplanned incidents were the main reasons for this mismatch. Periods with unusual occurrences were excluded from the analysis. Similarly, periods with inclement weather conditions (i.e., heavy rain) were also excluded from the analysis. These periods are shown in Tables 3.3.1 through 3.3.4 with white cells (no shading).

The average speed was calculated for the morning peak period (6 to 11 a.m.) and afternoon peak period (3 to 7 p.m.). These values are then compared with the corresponding values on other days and weeks using t-tests and Wilcoxon rank-sum tests to evaluate the effect of various enforcement strategies on the average speed. Note that while the t-test assumes a normal distribution for the underlying speed population, the Wilcoxon rank-sum test is a nonparametric test with no assumption on the underlying distribution.

In addition to the average-speed analysis, the effects of each enforcement strategy on the number of citations were studied. The NNC (see Equation 2.3.1) was used for this analysis. Note that to have a fair comparison, the average number of tickets and warnings per patrolling unit were also compared for various strategies. Moreover, the temporal effects of each enforcement strategy were investigated. To study the time halo, the data collection was continued for at least 2 weeks after complete cessation of the enforcement at each study segment.

3.4 EFFECTS AT TREATMENT LOCATIONS

In this section, the effects of each enforcement strategy on the average speed are discussed. To attain a better understanding of the effects of different enforcement strategies on the average speed, separate analyses are provided for weekdays and weekends. In the following sections, the effects of enforcement strategies on the four segments during different time periods are discussed separately.

3.4.1 Study Area Chicago: I-55, I-57, I-94 (Weekdays)

Analyzing various resource-allocation strategies, a main objectives of this study, was accomplished by applying the stationary covert strategy to three segments in Chicago. Four weeks of active enforcement with various numbers of patrolling units were planned for each segment. Unfortunately, the actual enforcement covered only 2 days per week from 5 a.m. to 1 p.m. This period covered only the morning peak period, and no enforcement was applied during the afternoon peak period. This lack of data naturally imposes some restriction on the analysis.

3.4.1.1 Morning Peak Period

The interval between 6 and 11 a.m. is considered the morning peak period in the calculations. Figure 3.4.1 presents the daily and weekly average speeds on the three segments during the morning peak period. The effects of various enforcement intensities on the average speed can be determined from this figure. As shown in Table 3.2.1, the first week of enforcement on I-55 started with four patrolling units. A 17% reduction in the average speed was observed during that week. This value is 7% for I-57 and 16% for I-94, where enforcement took place with one and two patrolling units, respectively. On the basis of the t-test values from Tables 3.4.1 and 3.4.2, all the differences are statistically significant.

The average speed before the start of the enforcement on I-55 was 6.36 mph lower than on I-94. This observation explains why the average speed reduction on I-94 was similar to that attained on I-55 with fewer patrolling units. In essence, it is difficult to reduce the average speed when it is already low.

Overall, the results clearly show the effect of high-intensity enforcement on the average speed reduction. Using more patrolling units results in a greater reduction in the average speed. The enforcement continued in the second week with two patrolling units on all three segments. No change in average speed was observed on I-94 and I-57 in comparison to the previous week. However, the average speed increased 9% on I-55. The main reasons could be the low average speed (compared to the speed limit) and possibly some sensor problems on this segment. It is also important to note that although this increase in average speed was observed on I-55, the difference is not statistically significant (see Tables 3.4.1 and 3.4.2).

Because no enforcement was carried out during the fourth week, the average speed increased by 11, 12, and 14% on I-55, I-57, and I-94, respectively. After resuming the enforcement with two patrolling units during the seventh week, 8 and 6% reductions in average speed were observed on I-55 and I-57, respectively. No statistically significant reduction in average speed was observed on I-94.

The last week of enforcement continued with different enforcement intensities on all three segments. The speed limit was enforced by one, two, and four patrolling units on I-55, I-57, and I-94, respectively. A 3% reduction in average speed was observed on I-55, while the reduction on I-57 was only 2%. An average speed reduction of 4% was observed on I-94 (with four patrolling units).

After the last day of enforcement, the average speed reverted to its original value on I-57 and I-94. However, the average speed on I-55 remained low for 2 weeks before reverting to its original value. It is also important to note that due to the very limited active enforcement on these three segments, no time halo is expected on these segments.

The t-test (Table 3.4.1) and Wilcoxon rank-sum test (Table 3.4.2) indicate that the average speed of the *before* period (average of the first 3 weeks) was higher than the average speed of all weeks with active enforcement. This difference is statistically significant at the 99% confidence level. This observation confirms that the enforcement chain had a positive effect on reducing the average speed.

Figure 3.4.2 shows the cumulative speed distribution for the 10 weeks of study on the three segments. The position of the curves can be used to determine the effects of enforcement on the average speed. The figure clearly reveals that the cumulative distribution curves were shifted to the left by the presence of enforcement. The Kolmogorov-Smirnov test is used to check whether the differences between the distributions are statistically significant. The results are presented in Table 3.4.3.

As shown in Figure 3.4.2, the enforcement applied was found to be an effective way of increasing safety and reducing speed; however, it could have some negative effects on the traffic stream as well. Figure 3.4.2 reveals a speed pattern similar to a breakdown formation during the morning peak period for some weeks with active enforcement (e.g., week 5 on I-55). This pattern could occur because of abrupt changes in the speed of vehicles when their drivers noticed the presence of a patrolling unit. Such behavior could trigger shock waves that could eventually lead to a breakdown formation. Additional investigation of driver behavior in such situations would be required to confirm this finding.

The results of the data analysis revealed that starting with high-intensity enforcement and lowering the intensity (the case of I-55) could achieve more favorable outcomes than starting with low intensity and subsequently increasing it (the case of I-94). Enforcement with constant intensity (the case of I-57) also produced reasonable outcomes. However, it is difficult to draw definitive conclusions about the advantages and disadvantages of the three resource-allocation strategies because data are limited. It is also important to note that the volume in all three sections remained the same before, during, and after the enforcement.

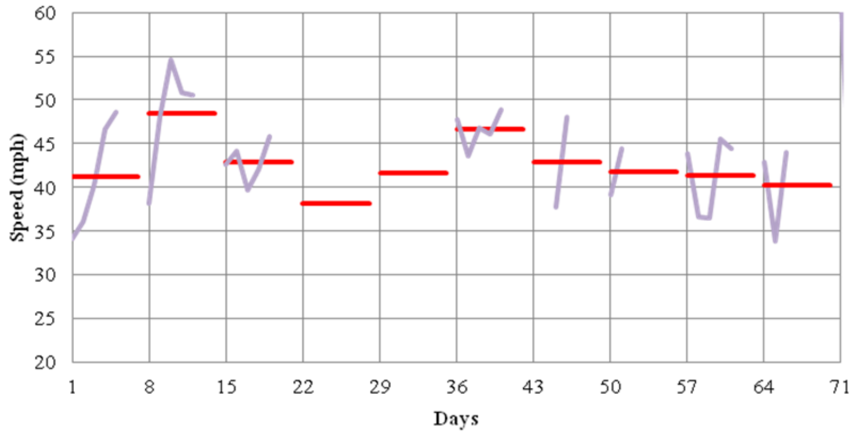
3.4.2 Study Area Chicago: I-55, I-57, I-94 (Weekends)

As mentioned previously, the enforcement on these three segments covered only 2 weekdays per week. The weekends did not receive enforcement on these segments, thereby precluding any conclusion on the effect of enforcement during the weekends.

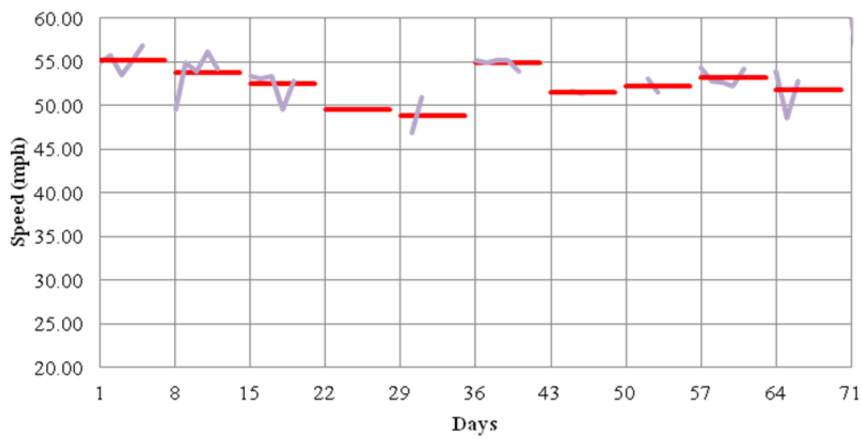
3.4.3 Study Area East St. Louis: I-55/I-70 (Weekdays)

Identifying the most effective patrolling strategies, a main objective of this study, was pursued by enforcing three different strategies on I-55/I-70 in East St. Louis. This objective, along with several others, was previously pursued in the pilot study. However, this new enforcement plan explicitly focused on the effect of various patrolling strategies. Six weeks of enforcement were planned on I-55/I-70. Three different enforcement strategies (circulating, stationary overt, and stationary covert) were chosen, and 2 weeks of enforcement were planned for each strategy. Note that the enforcement covered both morning and afternoon peak periods. The enforcement plan was discussed in detail in Section 3.2.

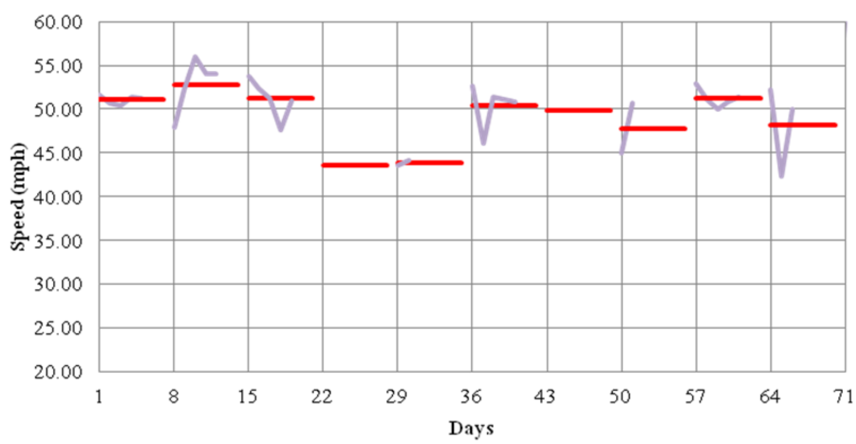
It is important to note that the stationary overt strategy was applied for only 3 days (instead of 2 weeks); the other two strategies were applied for the entire 2 weeks.



(a)

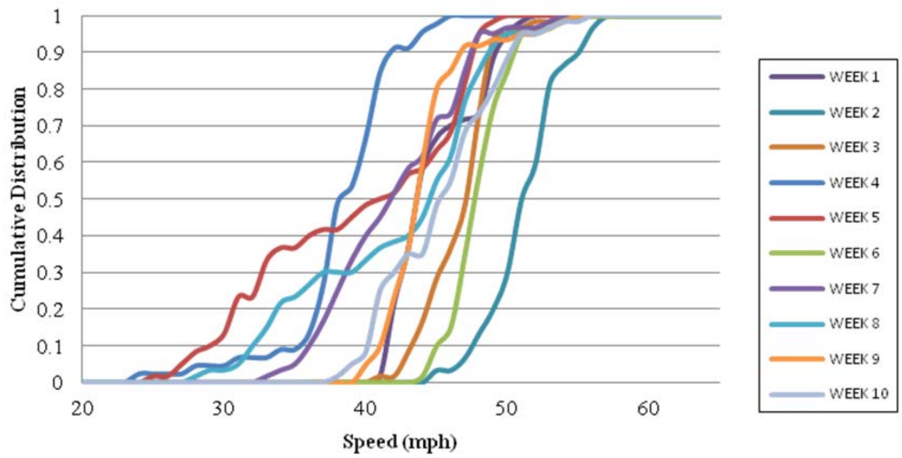


(b)

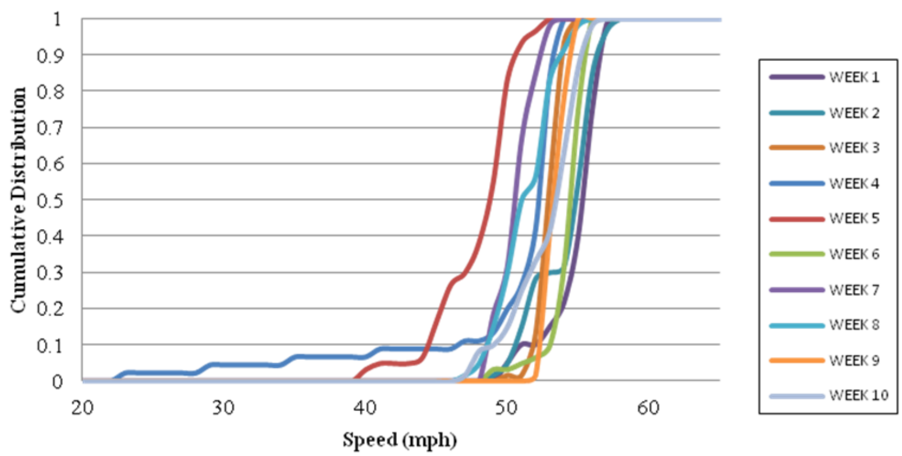


(c)

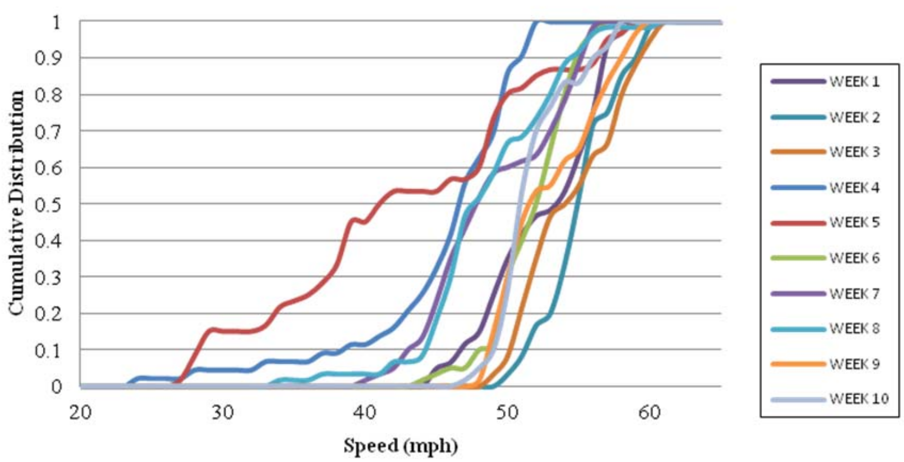
Figure 3.4.1 Daily average speed (purple) and weekly average speed (red) during the morning peak hours for 10 weeks of study on (a) I-55, (b) I-57, and (c) I-94.



(a)



(b)



(c)

Figure 3.4.2 Cumulative speed distribution during the morning peak hours for 10 weeks of study on (a) I-55, (b) I-57, and (c) I-94.

3.4.3.1 Morning Peak Period

The interval between 6 and 11 a.m. is considered the morning peak period in the calculations. Figure 3.4.3 presents the daily and weekly average speeds on the segment during the morning peak period. As shown in this figure, the average speeds during the third and fourth weeks (circulating strategy) is clearly higher than the average speeds during the eleventh and twelfth weeks (stationary covert strategy). Thus, the stationary covert strategy was more effective than the circulating strategy in reducing the average speed.

By considering the average speed during the *before* period, the maximum speed reduction from the circulating strategy was achieved during the second week of implementing this strategy (1.4% reduction). The reduction was 3% for the stationary covert strategy, which was achieved during the first week of implementing this strategy. Unfortunately, the data obtained during the eighth week are not reliable (owing to the lack of enforcement), and no conclusion can be drawn regarding the effectiveness of the stationary overt strategy.

Table 3.4.4 presents the t-test results. As shown in Figure 3.4.3 and this table, the average speed started to increase after the end of enforcement in the fourth week. The difference between the average speed during the first 2 weeks and the average speed during the fifth week is statistically significant, confirming the existence of a time halo in this study. The average speed eventually reverted to its original value (its value before the start of the enforcement) after the tenth week. The t-test value is 0.38 for the difference between the average speeds during the first and tenth weeks, which suggests that differences between the mean values are not statistically significant.

The results of the Wilcoxon rank-sum test (Table 3.4.5) are slightly different from the t-test results. On the basis of the Wilcoxon rank-sum test, the difference in the average speeds between the first and tenth weeks is statistically significant. The average speed distribution curve (Figure 3.4.4) of the tenth week is also on the left-hand side of the average speed distribution curve of the first week. The Kolmogorov-Smirnov test (see Table 3.4.6) results also confirm the difference between these two distributions.

Figure 3.4.3 clearly shows the shift in the cumulative distribution curves to the left because of the enforcement. It is also obvious that the stationary covert method was more effective than the circulating method in this regard.

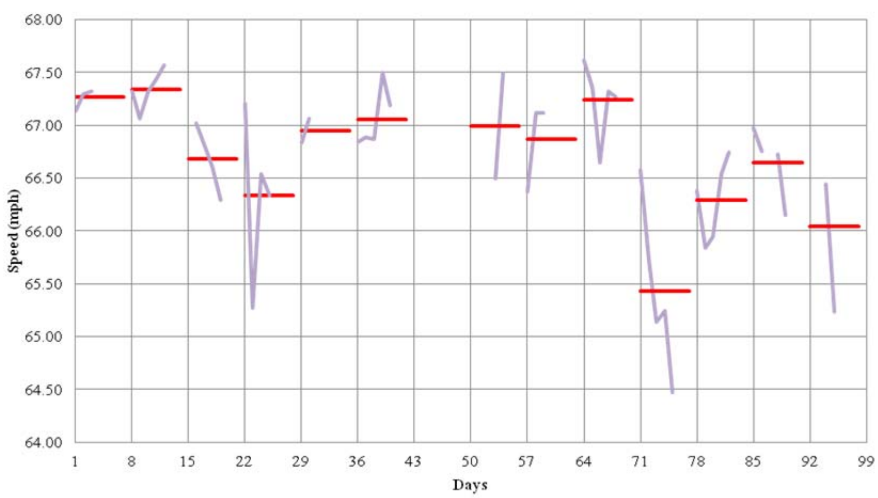


Figure 3.4.3 Daily average speed (purple) and weekly average speed (red) during the morning peak hours for 14 weeks of study on I-55/I-70.

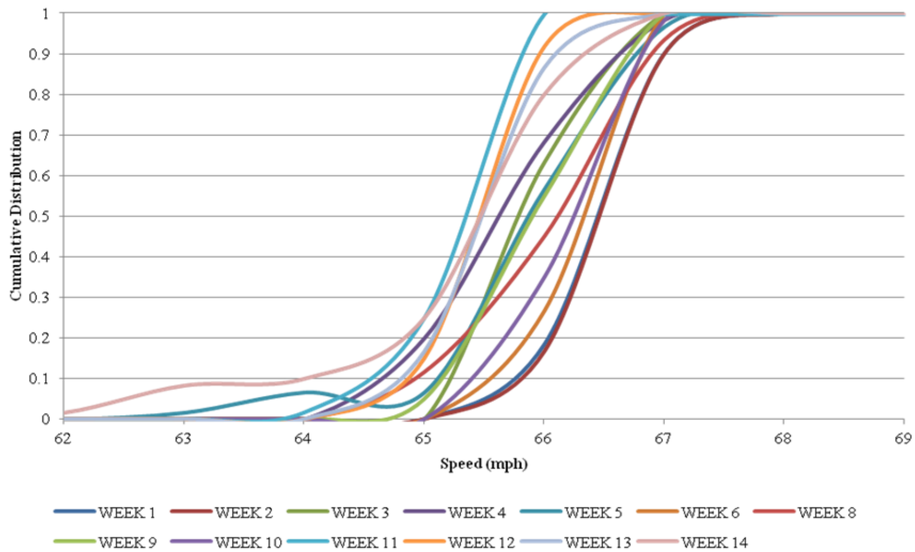


Figure 3.4.4 Cumulative speed distribution during the morning peak hours for 14 weeks of study on I-55/I-70.

3.4.3.2 Afternoon Peak Period

The interval between 3 and 7 p.m. is considered the afternoon peak period in the calculations. Figure 3.4.5 presents the daily and weekly average speeds on the segment. As shown in this figure, the average speeds during the third and fourth weeks (circulating strategy) are clearly higher than the average speeds during the eleventh and twelfth weeks (stationary covert strategy). Thus, the stationary covert strategy was more effective than the circulating strategy in reducing the average speed. By considering the average speed during the *before* period, a slight reduction in the average speed was observed during the fourth week. However, the circulating strategy had no significant impact on the average speed overall. More explicitly, as shown in Table 3.4.7, the difference between the average speeds in the second and third weeks is not statistically significant.

By contrast, the stationary covert strategy successfully reduced the average speed by 1.6%. The average speed started to increase after the end of the enforcement in the twelfth week. It is noteworthy that data from the eighth week are not reliable (owing to the lack of enforcement), and no conclusion can be made on the effectiveness of the stationary overt strategy. However, the results show a reduction in the average speed during this week.

The results of the Wilcoxon rank-sum test are presented in Table 3.4.8. The results of this test are slightly different from the t-test. For instance, on the basis of the results of Wilcoxon rank-sum test, the average speed during the second week is statistically different from the average speed during the third week. However, the overall conclusion based on this test is still similar to that for the t-test which shows that the stationary covert strategy was more effective than the circulating strategy.

Figure 3.4.6 shows the cumulative speed distribution curves for 14 weeks of study on this segment. The graph clearly reveals the effects of enforcement on the speed distribution. For instance, the speed distribution was shifted to the left due to the enforcement during the eleventh and twelfth weeks. The Kolmogorov-Smirnov test (see Table 3.4.9) results confirm the difference between the distributions of the *before* period and the stationary covert enforcement period. It also confirms that the speed distribution did not change during the circulating enforcement period.

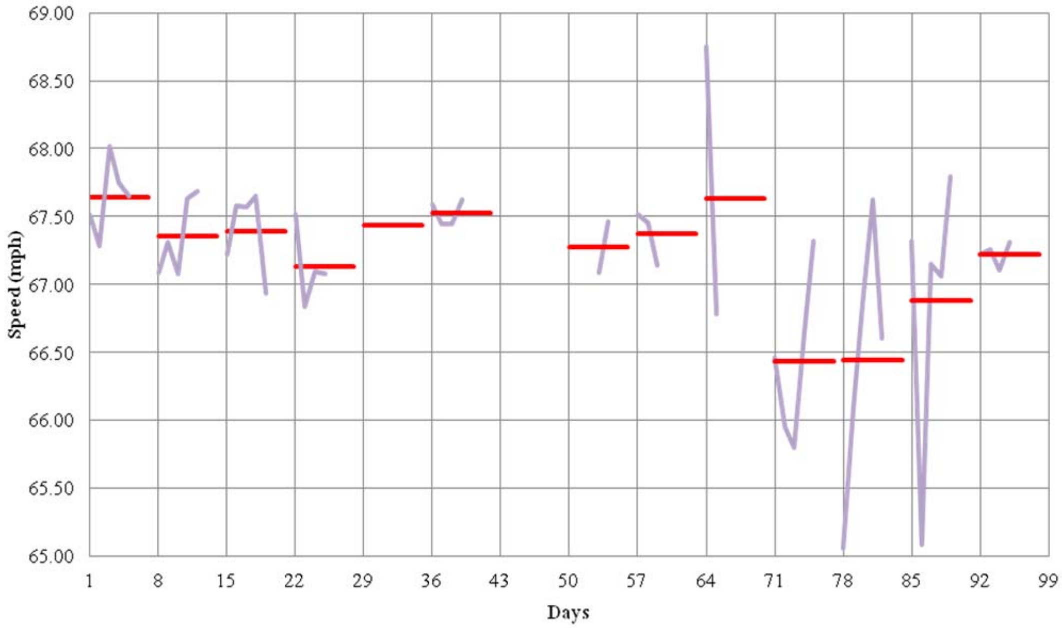


Figure 3.4.5 Daily average speed (purple) and weekly average speed (red) during the afternoon peak hours for 14 weeks of study on I-55/I-70.

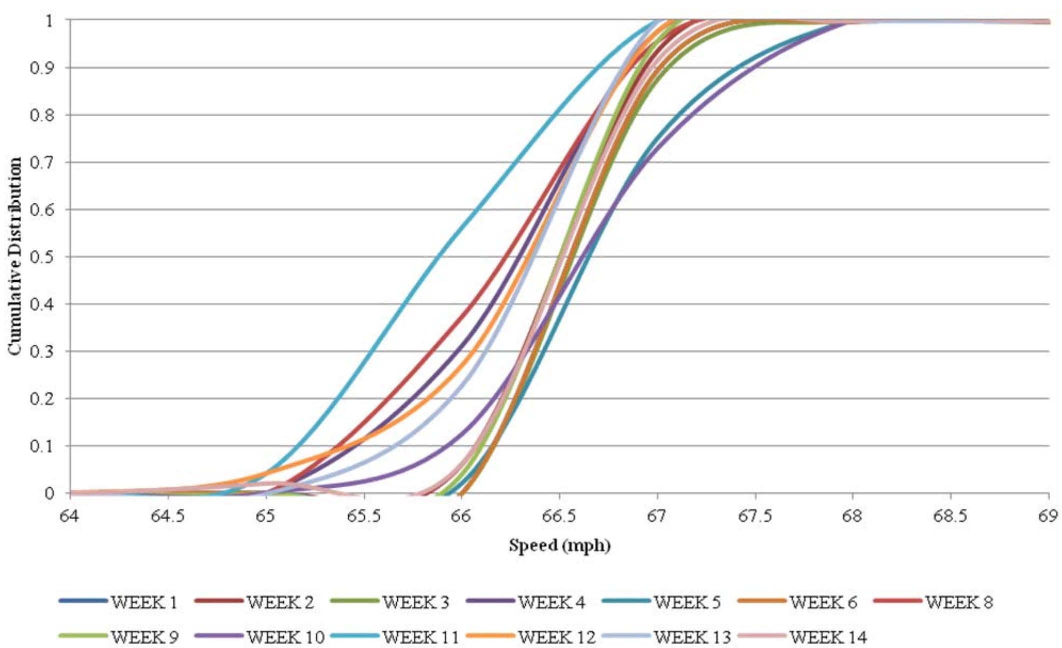


Figure 3.4.6 Cumulative speed distribution during the afternoon peak hours for 14 weeks of study on I-55/I-70.

3.4.4 Study Area East St. Louis: I-55/I-70 (Weekends)

The interval between 6 a.m. and 7 p.m. is considered the whole enforcement period. Figure 3.4.7 shows the daily and weekly average speeds on the segment during the active enforcement periods. Table 3.4.10 shows the t-test results for the differences between the average speeds. On the basis of the t-test results and Figure 3.4.7, the enforcement had very little effect during weekends on these segments. In other words, no clear pattern in the effect of enforcement on the average speed can be found.

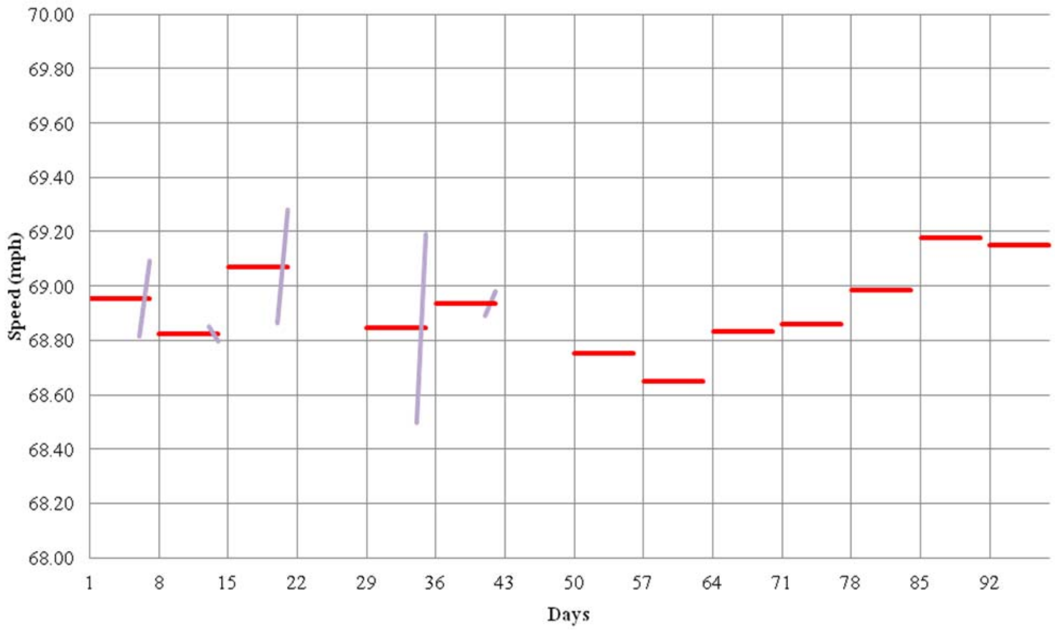


Figure 3.4.7 Daily average speed (purple) and weekly average speed (red) during the weekends for 14 weeks of study on I-55/I-70.

CHAPTER 4 COMPARISON OF ENFORCEMENT STRATEGIES

In this chapter, two comparisons between various enforcement strategies are presented. The first comparison is based on the average number of citations per hour. This value is presented for various enforcement strategies. The second comparison is based on the normalized number of citations (NNC). As mentioned previously, this measure captures the number of citations, as well as the average speed reduction. Furthermore, the effects of various enforcement intensities on the number of citations are analyzed.

Figure 4.1 shows the average number of citations per officer per hour for the four enforcement strategies (stationary overt, stationary covert, circulating, and chase car). On the basis of the t-test results, the differences among the values are small but statistically significant at the 95% confidence level.

As shown in Figure 4.1, the stationary covert strategy resulted in the highest rate of citations per hour. The citation rate for the chase car strategy was very close to that of the stationary covert one. However, the complexity in implementing the chase car method could lower its performance. The stationary overt strategy had the lowest rate among the four strategies.

On the basis of these results, it is recommended to use the stationary covert strategy when possible; otherwise, circulating is preferable to stationary overt. Overall, the chase car method is not particularly recommended; it is a complicated method but does not perform better than the stationary covert method.

Figure 4.2 presents the calculated NNC values for the four strategies. The results confirm that the stationary covert strategy was the most effective strategy. However, the superior effectiveness of the stationary overt strategy in terms of reducing the average speed makes this measure preferable when the main objective is speed reduction. The chase car strategy still had the same position among the four strategies. The chase car strategy has a positive effect on reducing the average speed due to the high concentration and visibility of police vehicles. On the basis of these results, it is recommended to use stationary covert strategy when possible and stationary overt or circulating, otherwise.

Figure 4.3 (a) shows the total number of citations per hour for the circulating strategy under three different intensities. From the figure, the higher number of patrol units would result in a higher number of citations. The increase in the number of citations is more than 100% when two patrol units were employed instead of one patrol unit. This increase is smaller when the number of patrol units was increased from two to four. Figure 4.3 (b) shows the average number of citations per hour per officer for the same data. It is clear that the optimal number of patrol units was two. The average number of citations per officer was the lowest in the case of four patrolling units. Assuming that this result extends to other enforcement strategies, it is recommended to use two patrol units on segments of 10 mi or less.

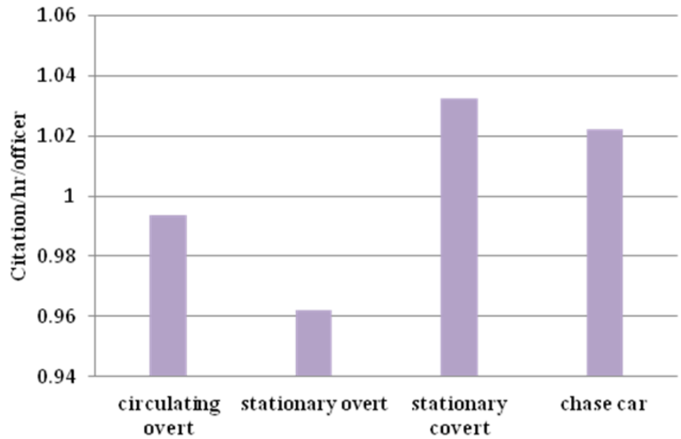


Figure 4.1 Average number of speeding tickets and warnings issued by each officer per hour.

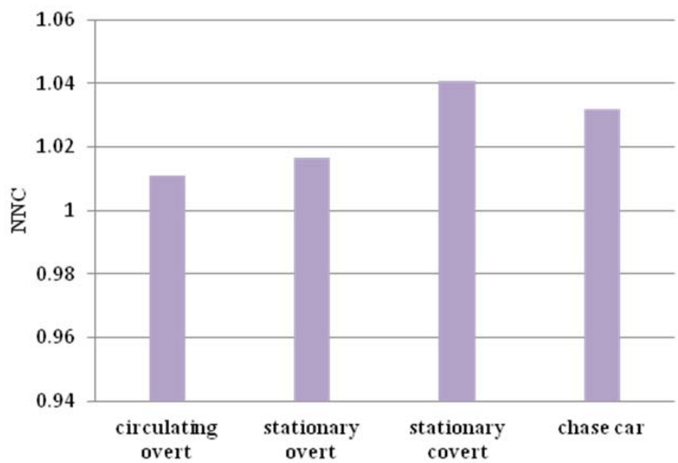
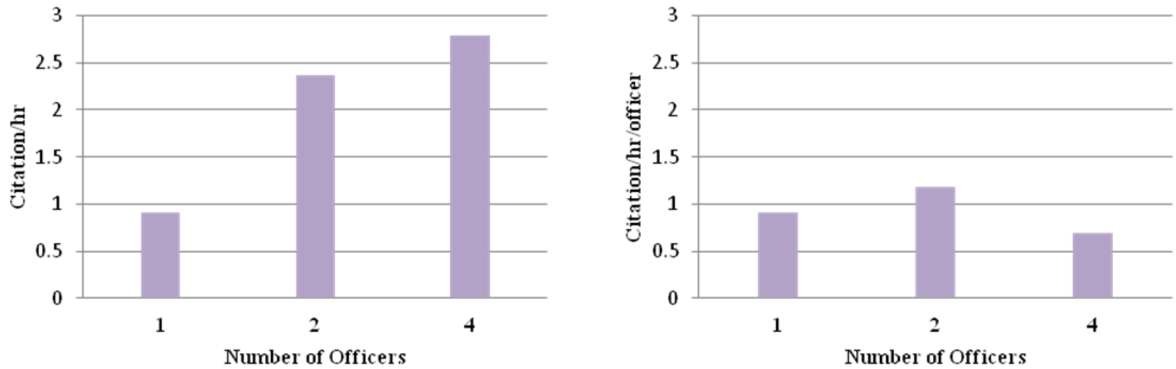


Figure 4.2 Effectiveness measure calculated based on equation 2.3.1 for each enforcement strategy (NNC refers to the normalized number of citations; see Section 2.3 for more details).



(a) (b)

Figure 4.3 Total number of citations per hour for the circulating overt strategy under three different intensities (a), versus average number of citations per hour per officer for the circulating overt strategy under three different intensities (b).

CHAPTER 5 OPTIMIZING THE RESOURCE ALLOCATION

Enforcing the speed limit is very costly; however, it results in substantial life-saving and injury reduction benefits for society. Although finding an appropriate resource-allocation plan is essential for the success of any enforcement program, designing an enforcement plan to maximize safety and minimize the enforcement cost is challenging to achieve and requires detailed knowledge of the enforcement process, life-saving and injury reduction benefits, resource allocation (including but not limited to patrolling locations, routes, and schedules), and the effects of various enforcement strategies on safety.

The main focus of this chapter is to present an optimization approach toward resource allocation. The approach presented is at its early stages, but it provides a basis that could be expanded upon with additional behavioral studies and data collection. In the following sections, the model formulation of the optimization approach is presented; and then the performance of the model is investigated through some sensitivity analyses.

5.1 MODEL FORMULATION

The notations used in the model are as follows:

N_C	:	Number of patrolling units using circulating as the patrolling strategy
N_{SO}	:	Number of patrolling units using stationary overt as the patrolling strategy
N_{SC}	:	Number of patrolling units using stationary covert as the patrolling strategy
C_C	:	Unit cost of the circulating strategy
C_{SO}	:	Unit cost of the stationary overt strategy
C_{SC}	:	Unit cost of the stationary covert strategy
h_C	:	Binary variable, equals 1 if the circulating strategy is used, 0 otherwise
h_{SO}	:	Binary variable, equals 1 if the stationary overt strategy is used, 0 otherwise
h_{SC}	:	Binary variable, equals 1 if the stationary covert strategy is used, 0 otherwise
$P_{Citation}$	:	Average price of each citation
V	:	Speed before introducing the enforcement (mph)
$N_{Citation}$	:	Total number of citations
$N_{Citation,C}$	:	Number of issued citations when using the circulating strategy
$N_{Citation,SO}$	:	Number of issued citations when using the stationary overt strategy
$N_{Citation,SC}$	:	Number of issued citations when using the stationary covert strategy

$$Min\left(\frac{8N_C C_C h_C + 8N_{SO}C_{SO}h_{SO} + 8N_{SC}C_{SC}h_{SC} - P_{Citation}N_{Citation}}{\Delta V}\right) \tag{5.1}$$

$s.t.$

$$\Delta V_C = f_1(N_C, V, h_C) \tag{5.2}$$

$$\Delta V_{SC} = f_2(N_{SC}, V, h_{SC}) \tag{5.3}$$

$$\Delta V_{SO} = f_3(N_{SO}, V, h_{SO}) \tag{5.4}$$

$$\Delta V = \Delta V_C + \Delta V_{SC} + \Delta V_{SO} \tag{5.5}$$

$$N_{Citation} = N_{Citation,C} + N_{Citation,SO} + N_{Citation,SC} \tag{5.6}$$

$$N_{Citation,C} = g_1(N_C, V, h_C) \tag{5.7}$$

$$N_{Citation,SC} = g_2(N_{SC}, V, h_{SC}) \tag{5.8}$$

$$N_{Citation,SO} = g_3(N_{SO}, V, h_{SO}) \tag{5.9}$$

$$h_C + h_{SO} + h_{SC} = 1 \tag{5.10}$$

$$N_C h_C + N_{SO} h_{SO} + N_{SC} h_{SC} \leq N_{TOTAL} \tag{5.11}$$

$$h_C, h_{SO}, h_{SC}: Binary\ \ variables \tag{5.12}$$

$$N_C, N_{SO}, N_{SC}: Integer\ variables \tag{5.13}$$

This model is a nonlinear integer programming formulation in which the objective function is set to minimize the enforcement costs and maximize the effectiveness of the enforcement on the average speed. Additional types of costs and benefits can be added to this objective function. For instance, the cost of patrolling should consider the cost of patrolling vehicles and the officers' salaries. The life-saving and injury reduction benefits and the crash cost should also be included in the model. However, considering these costs and benefits would require more detailed social and behavioral studies.

Constraints 5.2 to 5.4 reflect the relationship between the change in speed due to the enforcement, the speed before the start of the enforcement, and the number of patrolling units for each enforcement strategy. The same relationship between the number of citations, the speed before the start of the enforcement, and the number of patrolling units is included in constraints 5.7 to 5.9. Constraint 5.10 ensures the selection of just one strategy for each segment, and constraint 5.11 ensures the assignment of all patrolling units. Constraints 5.12 and 5.13 define the variable types.

The key issue in this model is to define the relationships in constraints 5.2, 5.3, 5.4, 5.7, 5.8, and 5.9. This task requires detailed knowledge of the effect of enforcement on the average speed (which was discussed in previous chapters) and the number of citations (which was also studied to some extent in previous chapters). The enforcement-related data from this study (especially during the statewide study) are very limited; however, based on the findings, it is still possible to create a model for some of these relationships. A longer study covering various combinations of methods and intensities is required to gain more confidence in these relationships.

5.2 SENSITIVITY ANALYSIS

On the basis of the available data, various models with different levels of complexity can be created to reflect these relationships. In this chapter, a simple regression model is used for the sensitivity analysis. It is important to note that no model can be generated for the stationary covert strategy because the data are limited. NLOGIT 4.0 was employed to build the regression models. The models' characteristics are as follows:

$$\Delta V_C = \underset{(447)}{0.354} N_C \tag{5.14}$$

$$\Delta V_{SO} = \underset{(6.402)}{1.680} N_{SO} \tag{5.15}$$

$$N_{Citation,C} = \underset{(4.070)}{0.199} N_C \tag{5.16}$$

$$N_{Citation,SO} = \underset{(4.085)}{0.120} N_{SO} \tag{5.17}$$

On the basis of these models, the optimization program was simplified as follows:

$$Min \left(\frac{N_C C_C h_C + N_{SC} C_{SC} h_{SC} - P_{Citation} N_{Citation}}{\Delta V}\right) \tag{5.18}$$

$\boldsymbol{s.t.}$

$$\Delta V_C = 0.354 N_C \tag{5.19}$$

$$\Delta V_{SO} = 1.680 N_{SO} \tag{5.20}$$

$$\Delta V = \Delta V_C + \Delta V_{SO} \tag{5.21}$$

$$N_{Citation} = N_{Citation,C} + N_{Citation,SO} + N_{Citation,SC} \tag{5.22}$$

$$N_{Citation,C} = 0.199 N_C \tag{5.23}$$

$$N_{Citation,SO} = 0.120 N_{SO} \tag{5.24}$$

$$h_C + h_{SO} = 1 \tag{5.25}$$

$$N_C h_C + N_{SO} h_{SO} = 4 \tag{5.26}$$

$$h_C, h_{SO}, h_{SC}: Binary\ \ Variables \tag{5.27}$$

$$N_C, N_{SO}, N_{SC}: Integer\ Variables \tag{5.28}$$

The model assumed four available patrolling units. The average cost of each citation is assumed to be \$135. This mixed-integer, nonlinear program was used in the sensitivity analysis; and it was solved by GAMS Rev 145. Figure 5.1 presents the relationship between the resource allocation and the patrolling cost. These results clearly reveal that the actual cost of patrolling can be an important factor in choosing the optimal enforcement strategy. In other words, it can have large impact on the outcome of the program. In this example, if the patrolling cost stays below $34/hr, the circulating strategy is the optimal method (minimizing cost while maximizing safety). After this point, the stationary overt strategy becomes the optimal method.

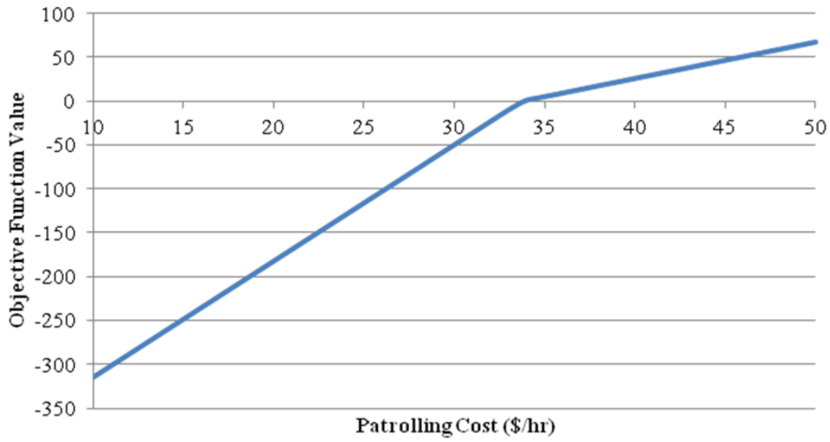


Figure 5.1 Objective function values for various patrolling costs.

The above model formulation considers all four available patrolling units in the calculations (see Equation 5.26). Relaxing this constraint introduces more complexity to the problem and would change the results. Figure 5.2 shows the sensitivity of the resource allocation to the patrolling cost when equation 5.26 is substituted with the following equation:

$$N_C h_C + N_{SO} h_{SO} = 4 \tag{5.29}$$

Because no constraint exists regarding the minimum value of the speed reduction, it is expected that the optimal enforcement plan will just use one patrolling unit to minimize the cost. By introducing this constraint into the optimization, the importance of the enforcement objective (the amount of the average speed reduction) becomes evident. The enforcement objective is another important factor that can determine the optimal strategy when the cost of the enforcement is not the only decision factor. Table 5.1 reveals that the optimal strategy directly depends on this constraint, which could be either of the two strategies. Note that the cost of enforcement was set to $15/hr.

Overall, it is very important to set appropriate objectives for the enforcement program to improve the roadway safety while considering the actual costs and benefits of the selected plan. It is also important to note that some costs as well as benefits of the enforcement program are not directly applied to the enforcement program itself. These costs and benefits are difficult to measure, and incorporating them in the optimization plan would require more detailed social and behavior studies.

CHAPTER 6 CONCLUSION AND SUMMARY OF FINDINGS

The main objectives of this study are to examine the influence of police patrolling methods on safety and to investigate the effectiveness of these methods in apprehending and citing the speed limit violators. Two studies were conducted, a pilot study and a statewide study. The main focus of the pilot study was to identify the effects of various enforcement strategies. The findings of the pilot study were used to design the statewide study. The statewide study focused on studying the effects of various enforcement strategies in more depth. In the following sections, the findings of these studies are presented.

6.1 PILOT STUDY

Two segments on I-64 and I-55/I-70 in East St. Louis were selected for the pilot study. This selection was based on several factors, including but not limited to the crash rate and the length of the segments. During the 17 weeks of data collection on the two segments, 7 weeks of active police enforcement were planned. The effects of four various police patrolling methods on the average speed were studied. Also, the effects of various enforcement intensities on the average speed were investigated. Finally a comparison between various police patrolling methods was conducted.

The speed data were collected by single-loop detectors on a 1-minute average basis. The speed data obtained were then aggregated to calculate the average speed during various time periods, including morning peak, afternoon peak, nonpeak, and the entire active enforcement period. The average speed for each of these periods was compared on a weekly basis for weekdays and weekends separately, as the traffic pattern is different on weekends from weekdays. The morning peak, nonpeak, and afternoon peak periods were compared for the weekdays; but the whole enforcement period was compared for the weekends. The difference between the average speeds was tested using the t-test and Wilcoxon rank sum test. The results revealed that the enforcement was more effective during the morning peak period in comparison with other time periods.

The enforcement strategies were the least effective during the afternoon peak periods. In some cases, the enforcement had no considerable effect on the average speed during this period (the case of I-64). The overall effect of enforcement during the nonpeak period was positive; however, some unexpected patterns were observed during this period (especially on I-64). The data in the fifth and sixth weeks on I-64 also revealed that the time halo can be used to reduce the enforcement cost. Using fewer patrolling units, while taking advantage of the time halo, could result in the same outcome as employing more units.

The average speed during weekends was higher than during weekdays. Considering the fact that drivers tend to drive around the speed limit in the presence of the police patrol, the enforcement resulted in a greater reduction in average speed, in comparison with weekdays. However, continuous enforcement was required to keep the average speed at a specific level. It is noteworthy that the most effective enforcement method in reducing the average speed was the stationary overt method (implemented during the fifth week on I-64).

In addition, the distribution of the average speed during each time period was studied. The Kolmogorov-Smirnov statistic was used to test whether the differences between these distributions are statistically significant. Overall, the cumulative distributions were shifted to the left (lower speeds) under the influence of enforcement.

Finally, an analysis of the duration of the time halo was presented. The study showed a time halo of at least 2 weeks on I-55/I-70. No time halo could be determined from the data on I-

64. However, it is expected that the time halo on I-64 had at least the same duration as that on I-55/I-70.

6.2 STATEWIDE STUDY

Four study segments were selected for the second portion of the study. One segment was on I-55/I-70 in East St. Louis and three segments were on I-55, I-57, and I-94 in Chicago. The selection was based on the findings of the pilot study, crash rate, length of the segments, etc. The speed data were collected by single-loop detectors on a 5-minute average basis. The data obtained were then aggregated to calculate the average speed during various time periods. Note that the morning peak and afternoon peak periods were compared for the weekdays, and the whole enforcement period was compared for the weekends. The differences between the average speeds were tested using t-tests and Wilcoxon rank sum tests.

The objective of the enforcement in Chicago was to identify the effects of various resource-allocation strategies and to study the time halo. Four weeks of enforcement with the stationary overt strategy, yet with different intensities, were designed for each of the three segments. After the last week of enforcement on each segment, 7 weeks with no enforcement were monitored. The results of the data analysis revealed that starting with high-intensity enforcement and lowering the intensity (the case of I-55) can have more favorable outcome in comparison with starting with the low intensity and increasing the intensity (the case of I-94). The enforcement with constant intensity (the case of I-57) also produced reasonable outcomes.

The actual enforcement just covered two days per week from 5 a.m. to 1 p.m. on the three selected segments in Chicago. Unfortunately, this precluded the ability to study the time halo.

The objective of the enforcement in East St. Louis was to identify the most effective enforcement strategy. Three different strategies (circulating, stationary overt, and stationary covert) were tested on this segment. Unfortunately, the stationary overt strategy was enforced for only 3 days; therefore, not enough data are available for this strategy. The other two strategies were compared for both weekdays and weekends. The findings indicated that the stationary covert strategy was more effective in reducing the average speed during the morning and afternoon peak periods. However, no clear pattern on the effect of enforcement on average speed was found.

In addition, the distribution of the average speed during each time period was studied. The Kolmogorov-Smirnov test was used to test whether the differences between these distributions are statistically significant. In general, the cumulative distributions were shifted to the left (lower speeds) under the influence of enforcement. However, in some cases traffic breakdown, which results in substantial loss of throughput, was observed during the weeks with active enforcement. This breakdown formation could happen because of an abrupt change in the speed of vehicles when the drivers notice a patrolling unit. The phenomenon could cause shockwaves, which could eventually lead to a breakdown formation in high traffic volumes. However, more detailed studies are required to confirm this finding.

6.3 COMPARISON OF ENFORCEMENT STRATEGIES

The enforcement strategies were also compared based on their ability to apprehend and cite violators. The results indicated that the stationary covert strategy was the most effective method, considering the ability to cite violators and reduce the average speed. Stationary overt and circulating overt strategies were more effective in reducing the average speed but less effective in citing the violators. It was also recommended to use two patrol units on the segments to increase the efficiency and effectiveness.

6.4 OPTIMIZING THE RESOURCE ALLOCATION

A mixed-integer, nonlinear optimization model to select the number of patrolling units was presented. A simplified version of the model was employed for the sensitivity analysis. The results showed the importance of considering the exact cost, including the social benefits, in the analysis. The sensitivity analysis also revealed that it is very important to set appropriate objectives for the enforcement.

6.5 SUGGESTIONS FOR ADDITIONAL RESEARCH

The study conducted here has provided useful insight and recommendations to enforcement agencies with regard to effective strategies of speed reduction and citation generation. These recommendations can be put to immediate use by the ISP in allocating resources to enforcement activities.

Although the study considered various parts of the state for the data collection, the researchers were limited by the lack of availability of speed-monitoring capability on many segments across the state. Nonetheless, sufficient representation from various locations was ensured by choosing segments from both Chicago and East St. Louis. Not unexpectedly, there are differences across locations and times of the day. Accordingly, it would be desirable to expand the observational basis for such findings, which would require additional speed-monitoring capabilities. Furthermore, it is clear that there is variability in how drivers respond to various enforcement methods and intensity; this is manifested in the prevalence of the time halo and the variation in its duration. This finding highlights the importance of studying user behavior under a wider range of enforcement stimuli. Such knowledge would create a more robust and transferable basis of fundamental knowledge that would underlie enforcement activities and their safety implications.

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APPENDIX TABLES

Table 2.2.1 Patrolling Strategies on Segment I-64

Location	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9
I - 64	No Enforcement	2 officers in 6 miles Design 3 Circulating Overt	2 officers in 6 miles Design 3 Circulating Overt	No Enforcement	2 officers in 6 miles Design 3 Stationary Overt	1 officer in 6 miles Circulating Overt	No Enforcement	No Enforcement	No Enforcement

Table 2.2.2 Patrolling Strategies on Segment I-55/I-70

Location	Week 10	Week 11	Week 12	Week 13	Week 14	Week 15	Week 16	Week 17
I - 55/ I - 70	No Enforcement	2 officers in 10.5 miles Design 3 Stationary Covert	4 officers in 10.5 miles Design 3 Circulating Overt	No Enforcement	4 officer in 10.5 miles Chase car (Covert)	No Enforcement	No Enforcement	No Enforcement

Table 2.3.1 Active Enforcement Hours on I-64 (shaded cells indicate the hours when at least one police vehicle was patrolling)

Date	Time											
	6:00–7:00	7:00–8:00	8:00–9:00	9:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00	13:00–14:00	14:00–15:00	15:00–16:00	16:00–17:00	17:00–18:00
6/27/2011	■	■	■	■	■		■	■	■	■	■	■
6/28/2011	■	■	■	■	■			■	■	■	■	■
6/29/2011	■	■	■	■	■					■	■	■
6/30/2011	■	■	■	■	■	■	■			■	■	■
7/1/2011	■	■	■	■	■	■		■		■	■	■
7/2/2011	■	■	■	■	■	■	■	■	■	■	■	■
7/3/2011	■	■	■	■	■	■	■	■	■	■	■	■
7/4/2011	■	■	■	■	■	■	■	■	■	■	■	■
7/5/2011	■	■	■	■	■		■	■		■	■	■
7/6/2011	■	■	■			■	■			■	■	■
7/7/2011	■	■	■			■	■			■	■	■
7/8/2011	■	■	■			■	■			■	■	■
7/9/2011	■	■	■			■	■			■	■	■
7/10/2011										■	■	■
7/18/2011	■	■	■	■	■	■	■	■	■	■	■	■
7/19/2011	■	■	■	■	■		■	■	■	■	■	■
7/20/2011	■	■	■	■	■	■	■	■				
7/21/2011												
7/22/2011	■	■	■							■	■	■
7/23/2011										■	■	■
7/24/2011	■	■	■	■	■		■	■	■	■	■	■
7/25/2011										■	■	■
7/26/2011										■	■	■
7/27/2011	■	■	■	■	■	■				■	■	■
7/28/2011	■	■	■							■	■	■
7/29/2011		■	■	■						■	■	■
7/30/2011										■	■	■
7/31/2011										■	■	■

Table 2.3.2 Active Enforcement Hours on I-55/I-70 (shaded cells indicate the hours when at least one police vehicle was patrolling)

Date	Time											
	6:00–7:00	7:00–8:00	8:00–9:00	9:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00	13:00–14:00	14:00–15:00	15:00–16:00	16:00–17:00	17:00–18:00
8/29/2011												
8/30/2011												
8/31/2011												
9/1/2011												
9/2/2011												
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9/20/2011												
9/21/2011												
9/22/2011												
9/23/2011												
9/24/2011												
9/25/2011												

Table 2.4.1 T-Test Results for Weekly Average Speed During Morning Peak Hours (reduction has positive value; see shaded cell)

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	30.18	21.58	18.71	57.57	49.80	57.18	25.66	33.99
2		0.00	–10.97	–14.97	21.91	20.08	18.59	–5.69	0.31
3			0.00	–4.02	36.65	32.02	34.43	5.30	12.61
4				0.00	42.51	36.45	40.95	9.32	17.28
5					0.00	1.17	–5.48	–29.42	–24.10
6						0.00	–5.74	–26.27	–21.46
7							0.00	–26.58	–20.75
8								0.00	6.63
9									0.00

Table 2.4.2 P-Values Resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During Morning Peak Hours

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.02	0.00	0.00	0.00	0.00	0.92	0.01
3			0.00	0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00	0.00
5					0.00	0.24	0.00	0.00	0.00
6						0.00	0.00	0.00	0.00
7							0.00	0.00	0.00
8								0.00	0.00
9									0.00

Table 2.4.3 P-Values Resulting from Kolmogorov-Smirnov Test, for Weekly average Speed During the Morning Peak Hours

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3			0.00	0.01	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00	0.00
5					0.00	0.14	0.01	0.00	0.00
6						0.00	0.00	0.00	0.00
7							0.00	0.00	0.00
8								0.00	0.00
9									0.00

Table 2.4.4 T-Test Results for Weekly Average Speed During the Nonpeak Hours (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	8.13	–2.88	9.49	41.72	45.88	43.41	17.84	15.31
2		0.00	–10.73	–2.50	24.34	29.55	27.66	7.18	2.48
3			0.00	14.87	48.63	51.90	49.17	21.53	20.72
4				0.00	42.54	46.29	43.29	13.15	9.06
5					0.00	8.37	6.15	–18.38	–32.33
6						0.00	–1.99	–24.38	–37.55
7							0.00	–22.32	–34.84
8								0.00	–6.84
9									0.00

Table 2.4.5 P-Values Resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During the Nonpeak Hours

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.06	0.00	0.00	0.00	0.00
3			0.00	0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00	0.00
6						0.00	0.00	0.00	0.00
7							0.00	0.00	0.00
8								0.00	0.00
9									0.00

Table 2.4.6 P-Values Resulting from Kolmogorov-Smirnov Test, for Weekly Average Speed During the Nonpeak Hours

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3			0.00	0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00	0.00
6						0.00	0.00	0.00	0.00
7							0.00	0.00	0.00
8								0.00	0.00
9									0.00

Table 2.4.7 T-Test Results for Weekly Average Speed During the Afternoon Peak Hours (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	–6.21	–0.07	–2.09	33.15	42.19	37.04	96.39	64.71
2		0.00	7.35	5.43	44.10	58.91	40.62	102.18	72.32
3			0.00	–2.40	36.53	48.13	37.86	98.59	67.46
4				0.00	40.07	53.67	38.98	100.36	69.82
5					0.00	3.73	20.52	78.19	40.92
6						0.00	19.35	78.77	40.74
7							0.00	42.82	8.48
8								0.00	–41.56
9									0.00

Table 2.4.8 P-Values Resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During the Afternoon Peak Hours

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.88	0.06	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3			0.00	0.04	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00	0.00
6						0.00	0.00	0.00	0.00
7							0.00	0.00	0.00
8								0.00	0.00
9									0.00

Table 2.4.9 P-Values Resulting from Kolmogorov-Smirnov Test, for Weekly Average Speed During the Afternoon Peak Hours

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3			0.00	0.06	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00	0.00
6						0.00	0.00	0.00	0.00
7							0.00	0.00	0.00
8								0.00	0.00
9									0.00

Table 2.4.10 T-Test Results for Weekly Average Speed During the Active Enforcement Period (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	19.15	1.64	24.14	43.88	33.96	7.99	10.22	17.71
2		0.00	–18.34	–8.47	25.08	2.28	–15.31	–15.08	–4.19
3			0.00	22.75	43.32	32.97	6.38	8.49	16.72
4				0.00	36.64	19.19	–17.02	–18.65	4.29
5					0.00	–27.11	–41.26	–41.41	–30.39
6						0.00	–29.07	–30.32	–8.41
7							0.00	1.51	12.99
8								0.00	12.73
9									0.00

Table 2.4.11 P-Values resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During the Whole Enforcement Period

Weeks	1	2	3	4	5	6	7	8	9
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00
3			0.00	0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00	0.00
6						0.00	0.00	0.00	0.00
7							0.00	0.00	0.00
8								0.00	0.00
9									0.00

Table 2.4.12 T-Test Results for Weekly Average Speed During the Morning Peak Period (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8
1	0.00	10.02	17.45	14.88	17.78	9.41	15.23	14.30
2		0.00	6.70	3.60	4.64	–2.91	2.25	4.09
3			0.00	–3.55	–3.33	–11.08	–5.82	–2.48
4				0.00	0.69	–7.74	–2.00	0.83
5					0.00	–10.14	–3.23	0.31
6						0.00	7.01	7.77
7							0.00	2.69
8								0.00

Table 2.4.13 P-Values Resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During the Morning Peak Period

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.40	0.00	0.00	0.18	0.00
3			0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.77
6						0.00	0.00	0.00
7							0.00	0.00
8								0.00

Table 2.4.14 P-Values Resulting from Kolmogorov-Smirnov Test, for Weekly Average Speed During the Morning Peak Hours

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.00z	0.00	0.00	0.00
2		0.00	0.00	0.36	0.00	0.00	0.01	0.09
3			0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.01	0.00
5					0.00	0.00	0.00	0.00
6						0.00	0.00	0.00
7							0.00	0.01
8								0.00

Table 2.4.15 T-Test Results for Weekly Average Speed During the Nonpeak Period (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.52	3.84	24.93	6.43	5.99	8.43	8.92
2		0.00	2.92	19.55	4.83	4.16	6.18	6.60
3			0.00	15.95	1.44	0.41	2.51	2.94
4				0.00	–18.65	–24.95	–20.59	–19.75
5					0.00	–1.56	1.25	1.81
6						0.00	3.45	4.13
7							0.00	0.68
8								0.00

Table 2.4.16 P-Values Resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During the Nonpeak Period

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.03	0.01	0.04	0.00	0.00	0.02
3			0.00	0.00	0.00	0.18	0.08	0.17
4				0.00	0.01	0.00	0.00	0.00
5					0.00	0.00	0.05	0.00
6						0.00	0.04	0.00
7							0.00	0.34
8								0.00

Table 2.4.17 P-Values Resulting from Kolmogorov-Smirnov Test, for Weekly Average Speed During the Nonpeak Hours

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.06	0.00	0.00	0.00
3			0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00
6						0.00	0.00	0.02
7							0.00	0.01
8								0.00

Table 2.4.18 T-Test Results for Weekly Average Speed During the Afternoon Peak Period (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8
1	0.00	10.40	–	23.35	–	6.37	–1.39	4.01
2		0.00	–	13.78	–	–6.14	–13.40	–6.12
3			–	–	–	–	–	–
4				0.00	–	–21.61	–27.63	–19.12
5					–	–	–	–
6						0.00	–9.74	–1.38
7							0.00	5.93
8								0.00

Table 2.4.19 P-Values Resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During the Afternoon Peak Period

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	–	0.00	–	0.00	0.01	0.00
2		0.00	–	0.00	–	0.00	0.00	0.00
3			–	–	–	–	–	–
4				0.00	–	0.00	0.00	0.00
5					–	–	–	–
6						0.00	0.00	0.18
7							0.00	0.00
8								0.00

Table 2.4.20 P-Values Resulting from Kolmogorov-Smirnov Test, for Weekly Average Speed During the Nonpeak Hours

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	–	0.00	–	0.00	0.01	0.00
2		0.00	–	0.00	–	0.00	0.00	0.00
3			–	–	–	–	–	–
4				0.00	–	0.00	0.00	0.00
5					–	–	–	–
6						0.00	0.00	0.06
7							0.00	0.00
8								0.00

Table 2.4.21 T-Test Results for Weekly Average Speed During the Active Enforcement Period (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8
1	0.00	12.87	–	12.25	2.57	7.79	–4.65	5.92
2		0.00	–	–2.22	–11.23	–7.20	–18.27	–6.29
3			–	–	–	–	–	–
4				0.00	–10.40	–5.69	–18.92	–4.80
5					0.00	5.49	–8.09	3.96
6						0.00	–14.75	–0.30
7							0.00	10.54
8								0.00

Table 2.4.22 P-Values Resulting from Wilcoxon Rank-Sum Test, for Weekly Average Speed During the Active Enforcement Period

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.00	0.00	0.00
3			0.00	0.00	0.00	0.00	0.00	0.00
4				0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00
6						0.00	0.00	0.00
7							0.00	0.00
8								0.00

Table 2.4.23 P-Values Resulting from Kolmogorov-Smirnov Test, for Weekly Average Speed During the Active Enforcement Period

Weeks	1	2	3	4	5	6	7	8
1	0.00	0.00	–	0.00	0.03	0.00	0.00	0.00
2		0.00	–	0.00	0.00	0.00	0.00	0.00
3			–	–	–	–	–	–
4				0.00	0.00	0.00	0.00	0.00
5					0.00	0.00	0.00	0.00
6						0.00	0.00	0.00
7							0.00	0.00
8								0.00

Table 2.4.24 Daily Crash Rate on I-64

Year	Total	PD	A-Injury	B-Injury	C-Injury	Fatal
2004	0.34	0.26	0.01	0.03	0.03	0.00
2005	0.46	0.39	0.01	0.02	0.03	0.00
2006	0.45	0.36	0.02	0.04	0.02	0.00
2007	0.32	0.29	0.01	0.01	0.00	0.00
2008	0.24	0.20	0.02	0.02	0.00	0.00
2009	0.22	0.18	0.01	0.02	0.00	0.00
2010	0.34	0.27	0.00	0.07	0.00	0.00
2011	0.17	0.14	0.00	0.03	0.00	0.00

Table 2.4.25 Daily Crash Rate on I-55/I-70.

Year	Total	PD	A-Injury	B-Injury	C-Injury	Fatal
2004	0.36	0.27	0.04	0.04	0.00	0.00
2005	0.43	0.39	0.02	0.01	0.01	0.00
2006	0.35	0.29	0.00	0.05	0.00	0.00
2007	0.28	0.23	0.02	0.02	0.00	0.01
2008	0.24	0.23	0.00	0.01	0.00	0.00
2009	0.29	0.27	0.00	0.00	0.02	0.00
2010	0.28	0.21	0.01	0.07	0.00	0.00
2011	0.18	0.14	0.00	0.00	0.00	0.04

Table 3.2.1 Patrolling Strategies for Different Weeks (shaded cells indicate presence of enforcement and white indicates no enforcement).

Location	week 1	week 2	week 3	week 4	week 5	week 6	week 7	week 8	week 9	week 10	week 11	week 12	week 13	week 14
I-55	No Enforcement	No Enforcement	4 Officers Stationary Overt	2 Officers Stationary Overt	No Enforcement	2 Officers Stationary Overt	1 Officers Stationary Overt	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement
I-57	No Enforcement	No Enforcement	1 Officer Stationary Overt	2 Officers Stationary Overt	No Enforcement	2 Officers Stationary Overt	4 Officers Stationary Overt	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement
I-94	No Enforcement	No Enforcement	2 Officers Stationary Overt	2 Officers Stationary Overt	No Enforcement	2 Officers Stationary Overt	2 Officers Stationary Overt	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement	No Enforcement
I-55/I-70	No Enforcement	No Enforcement	2 Officers Circulating	2 Officers Circulating	No Enforcement	No Enforcement	2 Officers Stationary Overt	2 Officers Stationary Overt	No Enforcement	No Enforcement	2 Officers Stationary Covert	2 Officers Stationary Covert	No Enforcement	No Enforcement

Table 3.3.1 Active Enforcement Hours on I-55
(shaded cells show the hours when at least one police vehicle was patrolling)

Date	Time							
	5:00–6:00	6:00–7:00	7:00–8:00	8:00–9:00	9:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00
7/16/2012								
7/17/2012								
7/23/2012								
7/25/2012								
8/8/2012								
8/9/2012								
8/13/2012								
8/14/2012								

Table 3.3.2 Active Enforcement Hours on I-57
(shaded cells show the hours when at least one police vehicle was patrolling)

Date	Time							
	5:00–6:00	6:00–7:00	7:00–8:00	8:00–9:00	9:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00
7/16/2012								
7/24/2012								
7/25/2012								
8/8/2012								
8/9/2012								
8/15/2012								
8/16/2012								

Table 3.3.3 Active Enforcement Hours on I-94
(shaded cells show the hours when at least one police vehicle was patrolling)

Date	Time							
	5:00–6:00	6:00–7:00	7:00–8:00	8:00–9:00	9:00–10:00	10:00–11:00	11:00–12:00	12:00–13:00
7/18/2012								
7/19/2012								
7/23/2012								
7/24/2012								
8/8/2012								
8/9/2012								
8/13/2012								
8/14/2012								

Table 3.3.4 Active Enforcement Hours on I-55/I-70
(shaded cells show the hours when at least one police vehicle was patrolling)

Date	Time								
	6:00–7:00	7:00–8:00	8:00–9:00	9:00–10:00	10:00–11:00	15:00–16:00	16:00–17:00	17:00–18:00	18:00–19:00
7/16/2012									
7/17/2012									
7/18/2012									
7/19/2012									
7/20/2012									
7/21/2012									
7/22/2012									
7/23/2012									
7/24/2012									
7/25/2012									
7/26/2012									
7/27/2012									
7/28/2012									
7/29/2012									
8/23/2012									
8/24/2012									
8/25/2012									
9/9/2012									
9/10/2012									
9/11/2012									
9/12/2012									
9/13/2012									
9/14/2012									
9/15/2012									
9/16/2012									
9/17/2012									
9/18/2012									
9/19/2012									
9/20/2012									
9/21/2012									
9/22/2012									

Table 3.4.1 T-Test Results for Weekly Average Speed During the Morning Peak Hours for 9 Weeks of Study on (a) I-55, (b) I-57, and (c) I-94 (reduction has positive value)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	10.20	10.21	7.11	3.81	7.50	7.78	12.54	12.17
3		0.00	4.96	2.06	–10.21	–0.04	1.05	3.47	4.60
4			0.00	–1.91	–9.09	–4.39	–3.46	–3.31	–1.99
5				0.00	–5.76	–1.87	–1.12	–0.58	0.47
6					0.00	5.89	6.28	13.42	11.80
7						0.00	0.90	2.31	3.48
8							0.00	0.99	2.22
9								0.00	1.89
10									0.00

(a)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	2.25	2.95	8.46	–1.98	4.67	3.08	1.42	3.68
3		0.00	2.31	10.37	–12.24	6.08	1.98	–2.67	2.89
4			0.00	0.52	–3.81	–1.41	–1.90	–2.61	–1.51
5				0.00	–16.04	–6.88	–7.91	–11.78	–5.82
6					0.00	16.98	9.91	11.30	8.70
7						0.00	–2.46	–8.99	–0.49
8							0.00	–3.73	1.24
9								0.00	4.16
10									0.00

(b)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	2.16	5.77	7.40	4.13	4.37	5.80	2.81	6.77
3		0.00	5.15	6.75	2.77	3.15	4.92	0.82	6.18
4			0.00	–0.26	–4.41	–3.93	–2.94	–4.97	–2.89
5				0.00	–5.73	–4.95	–3.55	–6.54	-3.53
6					0.00	1.06	3.17	–2.19	4.13
7						0.00	1.98	–2.69	2.55
8							0.00	–4.58	0.27
9								0.00	5.88
10									0.00

(c)

Table 3.4.2 Wilcoxon Rank-Sum Test Results for Weekly Average Speed During the Morning Peak Hours for 9 Weeks of Study on (a) I-55, I-57, and (c) I-94 (P-values)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4			0.00	0.09	0.00	0.00	0.00	0.00	0.00
5				0.00	0.00	0.00	0.03	0.00	0.00
6					0.00	0.00	0.00	0.00	0.00
7						0.00	0.85	0.00	0.00
8							0.00	0.11	0.00
9								0.00	0.02
10									0.00

(a)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	0.00	0.00	0.00	0.93	0.00	0.00	0.04	0.00
3		0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.80
4			0.00	0.56	0.00	0.12	0.00	0.00	0.00
5				0.00	0.00	0.00	0.00	0.00	0.00
6					0.00	0.00	0.00	0.00	0.00
7						0.00	0.00	0.00	0.00
8							0.00	0.00	0.00
9								0.00	0.22
10									0.00

(b)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
4			0.00	0.02	0.00	0.00	0.00	0.00	0.00
5				0.00	0.00	0.00	0.00	0.00	0.00
6					0.00	0.00	0.00	0.00	0.93
7						0.00	0.75	0.00	0.00
8							0.00	0.00	0.00
9								0.00	0.02
10									0.00

(c)

Table 3.4.3 Kolmogorov-Smirnov Test Results for Weekly Average Speed During the Morning Peak Hours for 9 Weeks of Study on (a) I-55, (b) I-57, and (c) I-94 (P-values)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3		0.00	0.00	0.00	0.04	0.00	0.00	0.00	0.00
4			0.00	0.00	0.00	0.00	0.00	0.00	0.00
5				0.00	0.00	0.00	0.16	0.00	0.00
6					0.00	0.00	0.00	0.00	0.00
7						0.00	0.16	0.00	0.00
8							0.00	0.00	0.01
9								0.00	0.00
10									0.00

(a)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
3		0.00	0.00	0.00	0.00	0.00	0.00	0.06	0.01
4			0.00	0.00	0.00	0.00	0.00	0.00	0.00
5				0.00	0.00	0.00	0.00	0.00	0.00
6					0.00	0.00	0.00	0.00	0.00
7						0.00	0.01	0.00	0.00
8							0.00	0.00	0.00
9								0.00	0.00
10									0.00

(b)

Weeks	2	3	4	5	6	7	8	9	10
2	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3		0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00
4			0.00	0.00	0.00	0.00	0.00	0.00	0.00
5				0.00	0.00	0.00	0.00	0.00	0.00
6					0.00	0.00	0.00	0.02	0.16
7						0.00	0.63	0.00	0.00
8							0.00	0.00	0.00
9								0.00	0.04
10									0.00

(c)

Table 3.4.4 T-Test Results for Weekly Average Speed During the Morning Peak Hours for 14 weeks of Study on I-55/I-70 (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	–0.86	6.54	7.62	2.90	2.36	–	2.29	3.62	0.38	10.83	9.96	10.36	8.76
2		0.00	9.47	10.14	4.20	4.03	–	3.28	4.96	1.57	11.97	12.90	11.96	10.11
3			0.00	2.00	–2.84	–4.85	–	–2.78	–1.82	–7.48	7.66	4.76	6.51	4.94
4				0.00	–4.23	–6.18	–	–4.05	–3.25	–8.47	6.35	2.50	4.88	3.46
5					0.00	–1.01	–	–0.28	0.78	–2.93	8.77	6.49	7.83	6.37
6						0.00	–	0.56	1.87	–2.39	9.94	8.84	9.35	7.67
7							–	–	–	–	–	–	–	–
8								0.00	0.98	–2.22	8.54	6.06	7.52	6.18
9									0.00	–3.73	8.13	5.45	7.04	5.64
10										0.00	11.16	11.15	10.89	9.13
11											0.00	–4.85	–2.06	–2.92
12												0.00	3.04	1.70
13													0.00	–1.03
14														0.00

Table 3.4.5 Wilcoxon Rank-Sum Test Results for Weekly Average Speed During the Morning Peak Hours for 14 Weeks of Study on I-55/I-70 (P-values)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	0.19	0.00	0.00	0.00	0.01	–	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.01	–	0.00	0.00	0.01	0.00	0.00	0.00	0.00
3			0.00	0.00	0.91	0.00	–	0.21	0.98	0.00	0.00	0.00	0.00	0.00
4				0.00	0.08	0.00	–	0.00	0.01	0.00	0.00	0.05	0.27	0.13
5					0.00	0.00	–	0.52	0.18	0.00	0.00	0.00	0.00	0.01
6						0.00	–	0.16	0.00	0.89	0.00	0.00	0.00	0.00
7							–	–	–	–	–	–	–	–
8								0.00	0.42	0.12	0.00	0.00	0.00	0.00
9									0.00	0.00	0.00	0.00	0.00	0.00
10										0.00	0.00	0.00	0.00	0.00
11											0.00	0.00	0.04	0.49
12												0.00	0.50	0.73
13													0.00	0.73
14														0.00

Table 3.4.6 Kolmogorov-Smirnov Test Results for Weekly Average Speed During the Morning Peak Hours for 14 Weeks of Study on I-55/I-70 (P-values)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	0.91	0.00	0.00	0.00	0.04	–	0.00	0.00	0.06	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.24	–	0.00	0.00	0.10	0.00	0.00	0.00	0.00
3			0.00	0.01	0.63	0.00	–	0.06	0.02	0.00	0.00	0.00	0.00	0.01
4				0.00	0.01	0.00	–	0.00	0.00	0.00	0.00	0.04	0.04	0.24
5					0.00	0.00	–	0.24	0.34	0.01	0.00	0.00	0.00	0.01
6						0.00	–	0.06	0.00	0.63	0.00	0.00	0.00	0.00
7							–	–	–	–	–	–	–	–
8								0.00	0.10	0.16	0.00	0.00	0.00	0.00
9									0.00	0.00	0.00	0.00	0.00	0.00
10										0.00	0.00	0.00	0.00	0.00
11											0.00	0.24	0.01	0.01
12												0.00	0.34	0.34
13													0.00	0.63
14														0.00

Table 3.4.7 T-Test Results for Weekly Average Speed During the Afternoon Peak Hours for 14 Weeks of Study on I-55/I-70 (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	5.29	4.35	9.03	2.87	1.95	–	5.73	4.70	0.08	16.52	9.01	9.13	6.74
2		0.00	–0.54	3.78	–0.99	–2.65	–	1.26	–0.23	–2.67	11.70	6.71	5.57	2.22
3			0.00	4.09	–0.53	–2.02	–	1.67	0.30	–2.30	11.66	6.88	5.79	2.59
4				0.00	–3.89	–6.02	–	-2.04	–3.80	–4.80	8.14	4.91	2.86	–1.12
5					0.00	–1.15	–	1.92	0.78	–1.75	10.43	6.82	5.59	2.69
6						0.00	–	3.49	2.31	–1.02	13.21	7.84	7.19	4.38
7							–	–	–	–	–	–	–	–
8								0.00	–1.40	–3.30	9.32	5.84	4.24	0.85
9									0.00	–2.48	11.41	6.74	5.58	2.32
10										0.00	9.85	7.37	6.21	3.89
11											0.00	0.44	–3.51	–8.50
12												0.00	–2.70	–5.36
13													0.00	–3.55
14														0.00

Table 3.4.8 Wilcoxon Rank-Sum Test Results for Weekly Average Speed During the Afternoon Peak Hours for 14 Weeks of Study on I-55/I-70 (P-values)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	0.00	0.10	0.00	0.58	0.84	–	0.00	0.00	0.55	0.00	0.00	0.00	0.00
2		0.00	0.00	0.00	0.00	0.00	–	0.01	0.72	0.02	0.00	0.00	0.01	0.06
3			0.00	0.00	0.59	0.16	–	0.00	0.00	0.32	0.00	0.00	0.00	0.02
4				0.00	0.00	0.00	–	0.88	0.00	0.00	0.00	0.29	0.38	0.00
5					0.00	0.74	–	0.00	0.00	0.67	0.00	0.00	0.00	0.05
6						0.00	–	0.00	0.00	0.55	0.00	0.00	0.00	0.00
7							–	–	–	–	–	–	–	–
8								0.00	0.00	0.00	0.00	0.55	0.86	0.00
9									0.00	0.01	0.00	0.00	0.00	0.25
10										0.00	0.00	0.00	0.00	0.04
11											0.00	0.00	0.00	0.00
12												0.00	0.64	0.00
13													0.00	0.00
14														0.00

Table 3.4.9 Kolmogorov-Smirnov Test Results for Weekly Average Speed During the Afternoon Peak Hours for 14 Weeks of Study on I-55/I-70 (P-values)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	0.00	0.22	0.00	0.03	0.82	–	0.00	0.00	0.08	0.00	0.00	0.00	0.01
2		0.00	0.01	0.01	0.05	0.00	–	0.00	0.48	0.00	0.00	0.08	0.05	0.08
3			0.00	0.00	0.33	0.65	–	0.00	0.00	0.01	0.00	0.00	0.00	0.14
4				0.00	0.00	0.00	–	0.48	0.00	0.00	0.05	0.33	0.33	0.00
5					0.00	0.08	–	0.00	0.03	0.03	0.00	0.00	0.00	0.05
6						0.00	–	0.00	0.00	0.05	0.00	0.00	0.00	0.03
7							–	–	–	–	–	–	–	–
8								0.00	0.00	0.00	0.01	0.22	0.14	0.00
9									0.00	0.00	0.00	0.03	0.00	0.22
10										0.00	0.00	0.00	0.00	0.00
11											0.00	0.00	0.00	0.00
12												0.00	0.65	0.00
13													0.00	0.00
14														0.00

Table 3.4.10 T-Test Results for Weekly Average Speed During the Weekends for 14 Weeks of Study on I-55/I-70 (reduction has positive value)

Weeks	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.00	2.35	1.37	–	1.90	0.37	–	2.06	3.67	1.24	1.92	–0.39	–2.28	–2.79
2		0.00	–0.54	–	–0.33	–1.90	–	0.70	1.98	–0.12	–0.13	–1.97	–3.76	–4.30
3			0.00	–	0.24	–1.04	–	1.02	2.24	0.26	0.39	–1.35	–2.96	–3.40
4				–	–	–	–	–	–	–	-	-	-	-
5					0.00	–1.49	–	0.90	2.19	0.09	0.17	–1.68	–3.43	–3.94
6						0.00	–	1.83	3.35	1.02	1.55	–0.62	–2.45	–2.94
7							–	–	–	–	–	–	–	–
8								0.00	0.85	–0.65	–0.75	–2.02	–3.27	–3.58
9									0.00	–1.59	–1.96	–3.27	–4.70	–5.12
10										0.00	0.03	–1.32	–2.59	–2.90
11											0.00	–1.74	–3.40	–3.87
12												0.00	–1.47	–1.80
13													0.00	–0.28
14														0.00

Table 5.1 Optimal Strategies Under Various Minimum Speed-Reduction Constraint (patrolling cost set to be $15/hr)

Minimum Speed Reduction (mph)	N_C	N_{SO}	Number of Citations	Expected Speed Reduction	Objective Function Value
0	1	0	0.20	0.35	–709.01
1	0	1	0.12	1.68	–358.21
2	0	2	0.24	3.36	–192.66
3	0	2	0.24	3.36	–192.66
4	0	3	0.36	5.04	–119.21
5	0	3	0.36	5.04	–119.21
6	0	4	0.48	6.72	–77.72

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