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Best Practices for INDOT-Funded Work Zone Police Patrols

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AND PURDUE UNIVERSITY

BEST PRACTICES FOR INDOT-FUNDED WORK ZONE POLICE PATROLS

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JOINT TRANSPORTATION RESEARCH PROGRAM

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16. Abstract

Transportation agencies across the U.S. are expending a great deal of effort to improve highway work zone safety. Among those efforts is a special fund for work zone enforcement established by the Indiana Department of Transportation (INDOT). The allocation of enforcement funding was based on expert knowledge and weights and scores applied to work zone characteristics considered relevant to traffic safety. The objective of the reported project was to develop a rational and defendable tool for programming police enforcement that maximizes the safety benefits of police enforcement in INDOT work zones.

To understand what affects work zone safety, the research team carried out an extensive literature review, designed field experiments to evaluate the effect of selected enforcement strategies on drivers' behavior in work zones, and developed speed models incorporating the effect of police enforcement. The estimated speeds were used to derive CMFs that express the effect of the police enforcement strategy on work zone safety. Finally, the research team combined all of the developed components in a method of predicting the costs and the safety benefits in works zones under various enforcement strategies. This last method was included in the optimization tool for programming police enforcement in a group of planned work zones.

The described project developed an optimization tool implemented in a Microsoft Excel spreadsheet with the OpenSolver add-in. The tool is flexible, straightforward, and easy to use. The user should be able to quickly become familiar with the required input, results, and obtained solution.

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EXECUTIVE SUMMARY

BEST PRACTICES FOR INDOT-FUNDED WORK ZONE POLICE PATROLS

Work zone safety is a major concern for transportation agencies, especially when more maintenance projects are needed for the aging U.S. highway system. As a part of ongoing efforts by the Indiana Department of Transportation (INDOT) to improve safety in the work zones operated by them, INDOT is funding a special police enforcement program whereby Indiana State Police (ISP) officers routinely patrol selected work zones. The objectives of this enforcement program are to deter speeding and aggressive driving, along with other dangerous driving behaviors, to ultimately reduce crashes and improve traffic operations within work zones.

However, funding for this special program is rather limited, as is knowledge of its effectiveness in reducing work zone crashes. A research study was deemed necessary to better understand how the INDOT-funded work zone police enforcement program can be used most effectively. INDOT subsequently commissioned the Center for Road Safety (CRS) at Purdue University to carry out this research study with the following objectives:

1. Attain a better understanding of work zone crashes;
2. Identify the most cost-effective work zone enforcement strategies; and
3. Develop a program to achieve the best possible safety benefits.

The two-year effort by CRS consisted of the following five tasks:

1. Conduct a literature review to learn the current knowledge on related topics;
2. Gather and study the known factors of work zone crash frequency to understand the safety issues in work zones and to identify high-crash work zones;
3. Conduct a work zone police enforcement experiment to identify various enforcement strategies and determine the most cost-effective strategies;
4. Develop crash modification factors (CMFs) for enforcement to link the previous two tasks of the research and enable enforcement programming; and
5. Develop a Police Enforcement Programming Tool (PEPT) to optimize work zone police enforcement activities.

The program developed by CRS achieved the main objectives of the study and meets INDOT's needs for work zone police enforcement programming. This study also added new insights to the current body of literature on this topic. In the following sections, all the efforts and findings of the study are briefly presented.

Literature Study

In the current body of literature, many studies have shown that, for the same location, the crash rate could be significantly higher during periods of construction compared to non-construction periods. However, studies that were concerned with crash severity had rather mixed results (i.e., some found higher severity during periods of construction while others concluded that there were no statistically significant differences). Various work zone crash modeling studies have identified several features that are likely to cause more crashes, which include but are not limited to greater exposure, lane closure, crossover, and high crash intensity. However, most of the past modeling studies either lacked detailed work zone information (e.g., cross-sectional features, traffic management strategies, etc.) or utilized a rather small sample size; either or both of these limitations could have greatly limited the power of those models and thus affected the results and conclusion.

The effect of police enforcement on the behavior of drivers has also been widely studied. Such enforcement strategies are generally divided into two broad categories:

1. Passive enforcement (visible enforcement), where the police vehicles are highly visible to the traffic and are mainly used to deter unlawful driving behaviors, and
2. Active enforcement (non-visible enforcement), where the police vehicles are inconspicuous to the traffic and are actively enforcing traffic laws.

More recently, as technology continues to advance and the cost of police enforcement becomes an issue, automated enforcement and other alternative strategies are becoming more popular. These non-police-involvement strategies have been studied both inside and outside work zones, and some of them were found to be very promising.

However, major issues have also been identified with police enforcement strategies. First, the effectiveness of enforcement can vary greatly across work zones, which requires that studies attempting to measure the effectiveness of such strategies must be very carefully designed. Unfortunately, very few studies accomplished that feat. Secondly, a compromise was found between the use of active and passive enforcement. Most studies found that passive enforcement had very good immediate effects and basically no residual effects, while active enforcement was found to have significant residual effects but less effective immediate effects. Also, some of the literature pointed out that passive enforcement should be accompanied by active enforcement; otherwise, the effectiveness of enforcement presence will be gradually compromised.

Work Zone Crash Modeling

In order to understand the mechanism of work zone crashes and to identify the work zones with the most crash reduction potential, the CRS estimated a work zone crash model. Since data limitation was the most outstanding issue identified from the current body of literature, CRS designed and conducted an INDOT project engineer survey to retrieve detailed work zone information for a first-of-its-kind work zone inventory database. An adequate sample size was obtained from this survey, and the database was assembled for the modeling analysis.

The model results not only confirmed some previous findings, but also gained some new insights:

1. Work zones with both high ($>$\$35,000/day $\times$ mile) and low ($<$\$10,000/day $\times$ mile) working intensities were found to experience more crashes. While it is intuitive that high intensity work zones would have increased crashes, which has been identified in previous research, an explanation for more crashes in the low intensity work zones is less intuitive. A potential explanation for the low intensity crashes is that more "relaxed" construction sites may encourage drivers to disrespect the traffic regulations in the work zone.
2. Work zone features, such as lane shifts and lane splits, were found to increase crashes, although the increase was not as dramatic as the high intensity work zone.

3. A monthly variation was identified: both the summer months (May to July) and the winter months (November and December) were found to experience an increase in crash frequency, after accounting for traffic volume.
4. Other road characteristics prior to the construction were also found to significantly affect crash frequency; for example, an urban work zone was found to have almost four times as many crashes compared to a rural work zone.
5. Work zones on freeways also witnessed more crashes than other types of work zones.
6. Work zones on roads with wider left shoulders and wider rights-of-way were found to have fewer crashes.

These results will facilitate identifying work zones with a high crash potential and thus allocating enforcement resources where they could achieve the best safety benefit.

Work Zone Police Enforcement Experiment

As noted from the literature review, although many studies have evaluated enforcement strategies (both police-involved and non-police-involved) in work zones, very few of them employed a systematic design. In the absence of good design, any effectiveness identified usually became "mixed" with local effects, and the comparison across strategies or research studies therefore became less meaningful.

To overcome this issue, a relatively small-scale, but carefully designed, experiment was carried out to evaluate the immediate effect of a small subset of selected enforcement strategies. The residual effect was not evaluated due to budget concerns. Two factors, the intensity of stationary police enforcement and the presence of a variable message sign (VMS) displaying an enforcement message, were evaluated. Different combinations of these two factors (along with no enforcement for comparison) were repeated in six work zones. Other variables, including work zone type, traffic volume, time of day, and vehicle type (car, single unit truck, and truck-trailer) were also included in the analysis. Advanced analysis methods were used in order to obtain the best results.

Again, the modeling output confirmed several previous findings, while the following new knowledge was also obtained.

1. Passive stationary enforcement was found to have a significant effect on speed reduction in all work zone categories. In freeway work zones with no lane or geometry restrictions, passive stationary enforcement was found to be the most effective at the beginning of a work zone, followed by inside, and in advance (within half a mile), and it did not have a significant effect at the end of a work zone.
2. VMS had a surprisingly significant effect when placed within one mile upstream of a work zone. The effectiveness of a VMS rivals a police car at its most effective location.
3. With limited observations, circulating patrol cars did not appear to have a significant effect in this study, which is consistent with the literature.
4. The effectiveness of the same enforcement strategies were found to differ in different work zones, which confirmed that the local effect is significant.

Based on the findings from the analysis, the following general recommendations were made regarding work zone police enforcement:

1. For any work zone, the first police enforcement unit should be passive stationary enforcement at the beginning of the work zone or at the beginning of the actual activity area.
2. Whenever available, VMS is strongly recommended to display an enforcement message.
3. If available, additional enforcement units should be used for active enforcement inside the work zone in order to reinforce the deterrent effect and maintain the authority presence.

All the results from this experiment were incorporated into the developed Work Zone Police Enforcement Programming Tool (PEPT) through integer optimization.

Work Zone Police Enforcement Programming

In the previous two sections, knowledge regarding work zone crashes and the effectiveness of police enforcement was gained. To make the knowledge useful for practice, the Police Enforcement Programming Tool (PEPT) was developed that incorporates the knowledge and automatically generates the most economically sound enforcement plan.

The core of this tool is an integer optimizer. As various enforcement strategies are available for each work zone and each month, the optimization is formulated so that, subject to the total budget and the police enforcement and VMS availability constraints, the maximum safety benefit is determined.

To enable this optimization, additional analysis is carried out to convert the speed reduction effects of police enforcement into crash reduction and then monetary values. The cost for police enforcement is also calculated. With proper user inputs, all the calculations and the optimization are completed automatically in the program, and the programmed enforcement strategy, along with all the economic aspects, are presented to the user. In addition, the user is given the flexibility to override the optimizer and incorporate "user-defined enforcement" manually to accommodate special enforcement needs.

This Work Zone Police Enforcement Programming Tool (PEPT) is the major practical contribution of this study as the convenience provided by this program ensures the successful implementation of all the findings from the research study. PEPT was delivered and demonstrated to INDOT and will be implemented in 2013.

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1. INTRODUCTION

Highway work zone safety has been a concern nationwide and will likely draw ever increasing attention as more highway funds are being invested in highway maintenance. Transportation agencies across the U.S. are expending a great deal of effort to improve highway work zone safety. Among those efforts is a special fund for work zone enforcement established by the Indiana Department of Transportation (INDOT). Typically, $1,000,000 is paid annually to the Indiana State Police (ISP) for work zone speed enforcement as a part of INDOT's efforts to tackle speeding and other dangerous behaviors in highway work zones and to improve the safety of highway construction workers.

This study is an integral part of INDOT's efforts to improve highway work zone safety as well. Prior to this research project, the allocation of enforcement funding was based on relevant expert knowledge, as the currently used methodology arbitrarily assigns weights and scores to relevant factors concerning work zone safety with the enforcement hours assigned according to the candidate work zones with the highest scores. The new methodology proposed by the Purdue Research team, whose development is reported in this report, is an important step towards rational and cost-effective programming of the enforcement activities.

The objective of the reported project was to review the relevant literature, collect data and conduct its analysis, and develop a rational and defendable tool for programming police enforcement that maximizes the safety benefits of police enforcement in INDOT work zones.

To achieve the objective, the Purdue Research Team identified four major tasks:

1. Review of the current literature on related topics to gain better understanding of work zone safety issues, to learn the current practices of work zone police enforcement, and to identify gaps in the current knowledge required for building the police enforcement programming tool.
2. Estimation of the safety performance of work zones. To distribute the enforcement resources properly, work zones with the highest crash frequency and severity needed to be identified. Historical crash data were used to estimate the work zone crash frequency models.
3. Evaluation of enforcement effectiveness. The most cost-effective enforcement strategies needed to be identified. While the direct measure of safety or enforcement effectiveness is almost impossible, a proper surrogate measure can be used. Speed, which is one of the easiest to measure and most widely used surrogate safety measure, was chosen. Speed can be easily measured in the field and readily converted into safety benefits.
4. Development of the programming tool based on the knowledge learned from both the literature review and the data analysis.

This report presents the efforts and findings of the four research components throughout this project. Chapter 2 presents the literature review on work zone safety modeling, enforcement practices, the effectiveness of speed reduction strategies, and the relationship between speed and safety. Chapter 3 provides details about the data collection for work zone crash modeling and several work zone safety models estimated with the collected data.

Chapter 4 presents the evaluation of the effectiveness of selected police enforcement strategies in INDOT work zones. Speed reduction was used to measure the effect of the police enforcement. The advanced statistical analyses utilized in the study, which provided statistically sound estimation of the speed reductions, are described. One of the models, called here "the Speed Rebound Model," was estimated to evaluate the spatial residual effect of the police enforcement activities. This consideration was important to assigning multiple police cars to long work zones.

Chapter 5 describes the programming tool developed. Chapter 3, Chapter 4, and a so-called power model (*1*) provided a sufficient basis for estimating the safety benefits of various police enforcement strategies in specific work zones. A linear integer programming technique is presented in this chapter that seeks the optimal combination of work zones and police strategies to maximize the total safety benefits within the available budget, manpower, and other resources.

Chapter 6 presents a summary of the research findings and conclusions.

This research report is supplemented with a programming tool implemented in MS Excel with the addition of OpenSolver (*2*), which is publically available software. A user's manual for the tool is also included (see Appendix 5).

2. CURRENT PRACTICE AND PAST RESEARCH

The literature review consisted of two parts: work zone crash modeling and current practices of police enforcement in work zones. The first part determined the research work to date that studied work zone crashes, which helped the research team develop a method to identify high-crash work zones that would be candidates for deployment of police enforcement to improve safety. In the second part, the current police enforcement practices and emerging new alternative strategies are summarized, as well as their effectiveness.

2.1 Modeling Work Zone Crashes

The literature review on work zone crash modeling was necessary in order for the research team to understand how various factors affect crash patterns in work zones and to subsequently identify the work zones that would benefit the most from police enforcement.

Figure 2.1 shows the trends in the number of fatal crashes in highway work zones during the last 20 years (*3*). Although the troublesome increase in work zone fatalities in comparison to other road sections has been reversed, the nearly 700 fatalities per year in highway work zones remains a toll too large to be ignored. Relatively recent literature on the subject is discussed in

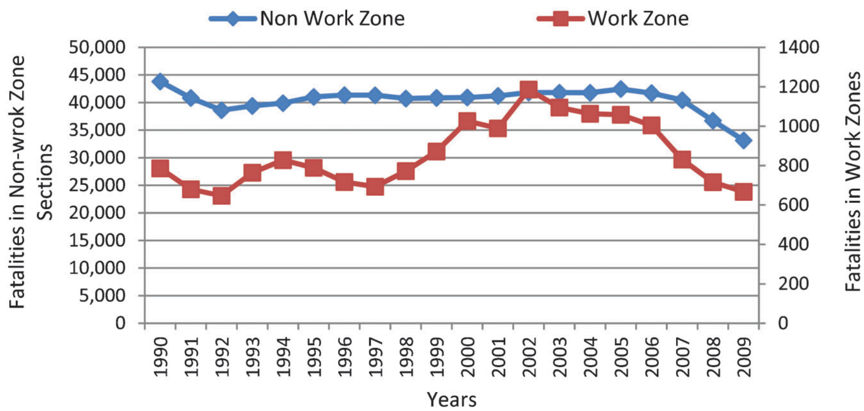

Figure 2.1 Fatal crashes in non-work zones and work zones. (Source: (*3*).)

this chapter, with an emphasis on work zones with modern design and traffic control devices.

2.1.1 Safety of Work Zones vs. Non-work Zones

The first question it was necessary to address was "Do work zones experience more crashes than in non-work zones?" Many studies have compared the crash rate before and during construction periods, and Ha and Nemeth (*4*) provided a summary review of these studies, which is shown in Table 2.1.

Although the extent of increase varied greatly, all of the previous studies included in Ha and Nemeth's review showed increases in the crash rate.

With the insight gained from Ha and Nemeth's study, the available individual studies, which may or may not have been part of the above study by Ha and Nemeth, were reviewed in detail for the current study. Early works on this topic showed that the crash rates in the studied work zones were higher than in non-work zone conditions. Rouphail et al. (*5*) studied work zone crashes in the Chicago area and found that the crash rates increased 88% and 69% in long-term and short-term work zones, respectively. Pal and Sinha (*6*) conducted a before-and-after study with a control group for Indiana. They found the crash rates were 37.2% higher during construction periods than during non-construction periods; and the increase for severe crashes was higher at 66.1%. More recently, Khattak et al. (*7*) found that non-injury and injury crash rates increased during construction periods by 23.8% and 17.4% in their study, but they could not confirm the statistical significance of these changes (t-statistic of 0.67 based on 36 pairs of observation). Also, Jin et al. (*8*) had difficulties confirming that the safety deterioration during the construction periods estimated by them was significant. The crash rates were higher during the construction periods on most of the studied highways, but very few of these differences were statistically significant.

A meta-analysis is needed to finally confirm to what extent work zones worsen highway traffic safety. Independently-obtained recent results, although rarely significant if considered independently, might provide sufficient evidence that highway work zones indeed contribute to deteriorating traffic safety.

2.1.2 Modeling Frequency of Crashes in Work Zones

A number of authors used statistical modeling to estimate the relationship between their studied variables and work zone crash frequency. Khattak et al. (*7*) found that the crash frequency increased with the traffic volume and the work zone length and duration.

Venugopal and Tarko (*9*) modeled rural freeway work zone crashes in Indiana with Negative Binomial models. They confirmed the length, time period, and AADT as adequate measures of exposure to risk in work zones. They also found that the relationship between the exposure and safety is non-linear and that work zones long in distance and duration generated lower crash rates than short work zones. In addition, they concluded that the work intensity and the presence of lane closures increased the crash frequency. The authors also studied traffic safety on the approaches to work zones.

Pal and Sinha (*6*) modeled freeway work zone crashes with OLS models, with a focus on two different lane closure strategies, but no statistically significant difference was found.

Harb et al. (*10*) concluded that males, local drivers, under 25 years old drivers, truck traffic, poor lighting conditions, and straight level geometry are associated with crash risk increases in work zones.

Garber and Zhao (*11*) studied different work zone sections and concluded that the types of crashes varied between them. Although rear-end crashes were predominant along the entire work zone, sideswipe crashes were the second most frequent type in work zone transition sections while single-vehicle (hit a fixed object) and angle crashes were more frequent inside the work activity areas.

Daniel et al. (*12*) analyzed fatal crashes using FARS data. Even though crashes from only three work zones in Georgia were included, they found that fatal crashes during construction periods were less affected by environmental factors (e.g., lighting conditions) and road geometry characteristics (e.g., horizontal and

TABLE 2.1
Accident Experience during Construction Period

Study	Study Site	Percent Change in Accident Rate
California (1972)	California	+21.4 to +7.0
Virginia (1976)	Virginia	+119.0
Georgia (Unpublished)	Georgia	+61.3
Midwest Research Institute (1978)	Colorado Georgia Michigan Minnesota Ohio New York Washington	+6.8
Ohio (1978)	Ohio	+7.0
Rouphail (1988)	Unknown	+88.0
New Mexico (1989)	New Mexico	+33.0 (Rural interstate) +17.0 (Federal aided primary) +23.0 (Federal aided secondary)

Source: (*4*).

vertical curves) and were more affected by traffic conditions (e.g., truck percentage) and by driver behaviors (e.g., following too close, driving too fast).

A recent Wisconsin study (*13*) linked the state crash database with the Wisconsin Lane Closure System (WisLCS). This provided a more complete picture of lane closure activities in Wisconsin together with other additional information about work zones. Unfortunately, the linked database does not include work zones without lane closure and the additional information is limited.

2.1.3 Injury Severity

In Ha and Nemeth's study (*4*), accident severity was also investigated for some of these studies, and the results are presented in Table 2.2.

The authors compared the changes of severe crashes as compared to the trend in overall accidents. There was great inconsistency among these ten studies, but overall it appears that higher severity injuries, especially fatalities, were over-represented in work zones.

Several studies dealt with work zone injury severity using different approaches that were studied in detail. Khattak et al. (*7*) and Venugopal and Tarko (*9*) modeled the frequency of different injury levels and demonstrated that crashes at these different levels exhibited similar behavior. Li and Bai (*14*) and Khattak and Targa (*15*) used logistic regression to model the probability of injury or fatal outcome conditioned on crash occurrence. Li and Bai (*14*) proposed a Crash Severity Index based on the logistic regression results. Although their approach could be debated, they identified a set of crash injury factors for work zone conditions. Khattak and Targa (*15*) studied truck crashes in work zones. Using ordered logit models, they found that a lane crossover and the proximity of a construction activity greatly increased the injury severity of crashes with trucks involved.

It can be concluded from the presented literature that the crash frequency or rate most likely increases during a construction period and changes the type and severity of crashes as well because work zone conditions are typically quite different from the conditions when a work zone is not present. There also seems to be evidence that traffic characteristics and driver behavior are important safety factors in work zones.

2.1.4 Other Aspects

In Ha and Nemeth's study (*4*), further investigation was conducted on crash patterns and causes. The

TABLE 2.2
Accident Severity Comparison (Change versus Overall Accident)

	Severity	
Study	**Fatal**	**Injury**
California (1972)	Higher	N/A
Virginia (1976)	Higher	Higher
Georgia (Unpublished)	Higher	Higher
Ohio (1978)	Higher	N/A
New Mexico (1989)	Same	Same
Graham (1977)	Same	Same
Flowers (1981)	Higher	Higher
Richards (1981)	Low	Low
Kentucky (1990)	Higher	Higher
Hargroves (1980)	Lower	Lower

Source: (*4*).

authors found from the available literature that the most prevalent crash pattern in highway work zones is hit fixed object, followed by rear end and same direction side swipe. Also, the contributing factors identified from the literature were summarized by Ha and Nemeth, as shown in Table 2.3.

As can be seen in Table 2.3, driver error was identified by all of the included studies as a contributing factor for construction work zone accidents, with unsafe speed identified by three out of the seven studies.

Another recent effort by Swansen and Knodler (*16*) used citation data to determine the causation for work zone crashes. Crashes involving slowing or stopped vehicles, changing lanes, entering traffic lane, first harmful impact on roadway, and most harmful impact with work zone equipment are significantly over-represented in work zones. On the other hand, crashes involving turning, leaving traffic lane, first harmful impact outside the roadway, and most harmful impact with roadside objects were significantly underrepresented. The authors admitted that crashes with citations are not representative of all work zone crashes.

2.2 Current Enforcement Practice

Police enforcement is applied worldwide in an attempt to improve traffic safety. A review done by Zaal (*17*) provided a comprehensive review on the global application of police enforcement activities with traffic safety in mind. That study was commissioned by the Netherland government to prepare a "state of the art" report on enforcement strategies related to road safety. The research effort was jointly carried out by the Institute for Road Safety Research (SWOV) and Monash University Accident Research Center (MUARC). This study included 550 publications around the world. More recently, an NCHRP project (*18*) provided a review for enforcement activities in highway work zones. This study mainly focused on U.S. studies and specifically on enforcement activities in highway work zones.

The findings from the both sources are summarized in the following sections along with other studies.

2.2.1 Objectives of Police Enforcement in Work Zones

Police enforcement is one of the most important methods for increasing driver compliance with traffic regulations to improve traffic safety and efficiency. The primary effects one can expect from police enforcement in work zones include:

- Remove DUIs from driving through work zones
- Reduce following too closely
- Control speeds
- Increase driver compliance with other work zone regulations
- Discourage aggressive driving
- Manage traffic incidents
- Improve driver alertness

Even though all these objectives are essential for improving traffic safety and the introduction of police enforcement in work zones could potentially achieve all these objectives to some extent, for research purposes, many of them are hard to measure. For instance, both aggressive driving and driver alertness are hard to measure or define, thus few studies have evaluated the effectiveness of police enforcement based on these objectives. One of these objectives, on the other hand, is very straightforward for both drivers and law enforcement officers to understand and is also easy for researchers to measure; that objective is speed. Maintaining a reasonable speed is one of the primary tasks for drivers, and they always should have perfect information about their speed. For police officers, the speed of a particular vehicle could be easily measured with their radar. For researchers, speed is also the easiest to measure. Thus, speed, and various derivatives of speed have been used in research works that evaluate the effectiveness of police enforcement.

2.2.2 Priority in Enforcement

Various police enforcement strategies have been used by law enforcement agencies for speed enforcement. Past research has shown that, based on drivers' behavior in regard to the presence of police enforcement, there are two major priorities in enforcement:

1. The immediate effect on speed reduction,
2. The lasting effect on changes in driving behavior.

In Zaal (*17*), the enforcement strategies are classified as visible and non-visible, while in the NCHRP project (*18*), they were referred to as passive and active

TABLE 2.3
Contributing Factors to Construction Zone Accidents

	Contributing Factors				
Study	**Driver Error**	**Unsafe Speed**	**Fail to Yield**	**Impaired**	**Follow Too Close**
Virginia (1976)	Yes	No	No	Yes	No
Ohio Rural (1978)	Yes	Yes	Yes	No	No
New Mexico (1989)	Yes	No	No	No	Yes
Flowers (1981)	Yes	No	No	No	No
Kentucky (1990)	Yes	Yes	No	Yes	No
Hargroves (1980)	Yes	No	No	No	No
Ohio Turnpike (1983)	Yes	Yes	No	No	No

Source: (*4*).

enforcement. Both the literature sources discussed the advantages and disadvantages of the two classes of enforcement strategies.

For immediate speed reduction, the common practice is to have highly visible police enforcement at some key locations in order to warn drivers and prevent dangerous behaviors like speeding, tailgating, or inappropriate lane changing. High visibility enforcement usually has a good effect on speed reduction when enforcement is present, but the halo effect has been found to be almost negligible (*19–21*). The effectiveness of highly visible police enforcement was also found to decline very quickly downstream of the police enforcement location by some studies (*22,23*), although no comparison study could be found between conspicuous and inconspicuous enforcement.

For the lasting effect on driving behavior, the key is to be "high probability" and "unpredictable" (*17,24–25*). Police enforcement should be dispersed without a certain pattern, thus drivers will sense a high risk of a citation and the corresponding consequences. Also, if drivers cannot predict where and when police enforcement will take place, a long lasting effect can be expected, both spatially and temporally. The downside is that a long lasting effect may take a long time period to form and the effect at certain key locations (e.g., work zones) may not be as significant. Also, one study (*23*) found the lasting effect of the police enforcement might not even be as good as a certain alternative strategy.

In general, experts agree that visible (passive) enforcement strategies lead to speed reduction and other behavior changes of a large percent of drivers—at least at the time and location of enforcement. Non-visible (active) enforcement, on the other hand, does not necessarily affect a large number of drivers, but such strategies lead to a higher perceived risk of getting apprehended among drivers who are stopped by police or witness such an event. Due to the research objective of this study on effective enforcement during temporary work zone conditions, we have selected the visible enforcement as more suitable.

2.2.3 Strategies of Enforcement

Various police enforcement strategies have been used for speed enforcement. NCHRP Report 3-80 (*18*) provided a comprehensive review of the state-of-the-practice enforcement strategies used in the U.S., along with the existing literature which has tested the effects of these strategies:

- **Circulating Patrol.** Circulating Patrol is one of the most often used strategies and is also known as mobile patrol, or simply patrol. Police vehicles patrol the targeted area (work zone), speeders are identified either by radar or by observation by the officer. Both marked police cars and unmarked police cars are used for this strategy.
- **Stationary Patrol—Non-Pursuit.** This strategy is also known as police presence in the Roadway Safety Training Institute's *Safe and Effective Use of Law Enforcement Personnel in Highway Work Zones: Pocket Guide* (*26*) and consists of stationing a police vehicle in the targeted area with their emergency lights flashing so as to be as visible as possible to the motorists. This strategy is for presence only, and the officers do not usually perform pursuit actions.
- **Stationary Patrol—Pursuit.** This strategy can also be used for police enforcement in (*26*). This strategy is also known as stationary police enforcement, which police vehicles are stationed at the targeted area, and the officer identifies speeders and carries out pursuits. After the pursuit, the officer returns to the targeted area. Both marked and unmarked police cars are used for this strategy.
- **Stationary Patrol—Multiple-Unit.** In this approach, multiple units enforce the same work zone, with the first unit (or several) identifying speeders and the last unit performing the pursuit. This strategy is especially suitable for work zones since pursuit inside the work zone might cause greater safety issues.
- **Police Traffic Controllers.** This strategy requires the police officer to be out of the police vehicle, to be as visible as possible to the motorist, and to perform eye contact or other communication to achieve the best effect of speed reduction.
- **Camouflaged Enforcement.** The first example of this camouflaged enforcement is the Florida Highway Patrol's "Operation Hardhat" (*27*), in which a police officer is camouflaged as a construction worker and monitors speed inside the work zone, while other units are performing pursuit outside the work zone. This approach is similar to the Stationary Multiple Units Enforcement approach, but is inconspicuous.
- **Automatic or Semi-Automatic Enforcement.** These strategies rely on speed cameras, which the legislation in State of Indiana (*28*) does not allow, thus these strategies will not be available for implementation in Indiana.

The most common enforcement approaches used in work zone locations are stationary patrols and circulating patrol. A 1999 survey of state departments of transportation (DOTs) and enforcement agencies carried out by Schrock et al. (*29*) found that 65 percent of state DOTs were using stationary patrols, while 45 percent indicated that they use mobile patrols. Some states reported using both types of strategies depending on conditions. Police traffic controllers were reported as being used in some work zones by 25% of the states. Typically, these specially arranged enforcement activities are funded by the transportation agencies (usually state DOTs). Twenty-five percent of the survey respondents confirmed that they increase the frequency of the patrols in work zone locations by establishing arrangement between the law enforcement agencies and the state DOTs. Also pointed out in the survey, New Jersey State Police maintains a unit of 35 state police officers who are assigned to work zone enforcement exclusively. They are also responsible for training other officers who participate in work zone enforcement on an overtime basis.

NCHRP Report 3–80 (*18*) also provides a summary of the effectiveness of these enforcement strategies, which is presented in Table 2.1, along with additional studies identified by the authors. There are other non-enforcement strategies used to reduce speed in work zones, which could be alternatives to traditional police enforcement or could be used to reinforce the effect of police enforcement. Such alternative strategies are shown below:

- Speed Photo Enforcement
- Dummy Enforcement Vehicles
- Drone Radar
- Variable Message Signs (VMS)
- Portable Speed Display Trailers
- CB Wizards (automated massage sent through citizen band radio)
- Rumble Strips
- Reduced Spacing of Channelizing Devices
- Transverse Pavement Marking
- Narrowed Lane Width

Some of these strategies have been used as countermeasures for speeding in work zones (*30–33*), while in some other studies these strategies have been used in combination with the traditional police enforcement (*21–23*). The primary motivation to use these alternative strategies is that the cost of such strategies is much lower when compared to police enforcement. Alternative strategies including Speed Photo Enforcement have been identified in (*17*). However, the effectiveness of some of these alternative strategies might not necessarily be inferior to that of the police enforcement, as will be demonstrated later. The application and effect of these strategies will be presented later in a separate section.

2.2.4 Effect of Enforcement Strategies

Many studies have reviewed the effectiveness of various enforcement strategies. However, the effectiveness needs to be measured differently for the two priorities. For immediate speed reduction, the effect can be easily measured at the scene when police enforcement is ongoing; but for the lasting effect, the measurement is not as straightforward. The spatial lasting effect could be measured downstream of the ongoing police enforcement (*20,22,23*), while the short term temporal effect could be measured immediately after the police enforcement ends (*20,34*).

Lasting effect. The majority of the studies concerning the lasting effect have shown that the residual effect (lasting effect or "halo effect") is mostly negligible. Such findings apply to both the temporal residual effect and the spatial residual effect.

Benekohal et al. (*20*) studied both the spatial and temporal residual effects. One hour of data were collected immediately after the police enforcement ended and were compared with data for the period when the police enforcement is in effect. The results show that the temporal residual effect of police enforcement was very negligible for cars, while for trucks there was some residual effect during the first hour after police enforcement ended. The study also suggested that the speed was consistently higher at the end of the work zone compared to the beginning of it; and all of the vehicles were being driven above the posted speed limit. Since the police enforcement strategy used in this study was mobile patrol, this not only suggests that no spatial residual effect was observed, but also that the effect of circulating patrol could be limited to the beginning portion of work zones.

Bloch (*22*) conducted a study to compare different alternative strategies (photo-radar and speed display board) on local street non-construction sections. The author collected speed information both at the treatment location and 0.2 mile downstream of the treatment. The findings were that the speed reduction effect of the speed display board, which was just 0.2 mile downstream, was only half as much as at the treatment location and was around 80% for photo-radar. However, when the speed display board was supplemented with police enforcement, the downstream effect was almost the same as at the treatment location.

A study by Medina et al. (*23*) studied the spatial residual effects of both police enforcement and alternative strategies in which all the speed were measured 1.5 miles downstream of the treatments. They found that the speed photo enforcement resulted in a speed reduction ranging from 0 to 3.3 mph, which was the most effective strategy in this study when compared to stationary police enforcement with/or speed displaying trailers, for which the effect of speed reduction ranged from -2.1 to 2.7 mph (-2.1 indicates an increase in speed). Such findings were a little surprising, but considering the speed was measured 1.5 miles downstream of the treatment, the increase of speed could be explained as a "rebound" effect.

In a recent study conducted by Wasson et al. (*34*) in Indiana, a very intensive police enforcement "blitz" was carried out with 12 enforcement vehicles (marked cars, unmarked cars, unmarked Ford Mustangs, motorcycles, and commercial enforcement units) in a 12- mile rural Interstate work zone. The authors found that the speed rebounded to the enforcement level within about one-half hour, and concluded that there is very little temporal residual effect for "visible active enforcement."

Interestingly, however, some of the alternative strategies show a better residual effect when compared to traditional police enforcement (*23*). Unfortunately, the legislation in Indiana prohibits photo speed enforcement, thus no further in-depth discussion could be provided about such alternative strategies.

Findings contradictory to these previous studies were reported by Hauer et al. (*35*) in Canada. The authors conducted an experiment involving police enforcement during normal roadway conditions (no road construction work). The interesting finding from this study was that sites with a large percentage of local drivers exposed to repeated enforcement exhibited a significant residual effect lasting about one week. Possible explanation to this significant temporal residual effect is the predominantly local traffic, which is unique as no other studies experienced similar conditions. In the Indiana TACT (Ticketing Aggressive Cars and Trucks) project, Tarko et al. (*36*) found that, even with a mix of local and pass-by traffic on two urban freeways segments, no clear temporal residual effect was detected.

In summary, regardless of the police enforcement used, the residual effect of the enforcement was negligible in highway work zones. It must be mentioned, that most of the enforcement strategies used in work zone were visible and many of the studies neither carried out long term enforcement nor measured the temporal and spatial residual effects.

Immediate effect (Police Enforcement Strategies). The focus of this study will be on the immediate speed reduction effect of police enforcement. A table was provided in NCHRP Report 3–80 (*18*), which summarizes the immediate effects of police enforcement in work zones from the current literature. Additional studies have been identified by the author, and the effects were added to the NCHRP Report 3–80 table, which is Table 2.4 that follows.

It can be seen from Table 2.1 that circulating enforcement had the least effect on speed reduction with the speed reduction consistently between 2 to 5 mph. Police traffic controller had mixed results; and while it had the highest level of speed reduction of 13 mph in the Richards et al. study (*37*), it also have the least speed reduction of 3 mph in the Noel et al. study (*38*). Stationary enforcement was the most used strategy in these studies and showed a consistently better effect compared to circulating enforcement. The Medina et al. study had negative effect with the speed actually increasing compared to no enforcement conditions. However, the speeds in Medina et al. (*23*) were measured 1.5 miles downstream of the enforcement so the effect measured was actually the spatial residual effect; and the immediate effect was not measured.

The Richards et al. study (*37*) evaluated a variety of speed reduction strategies in six work zones from different roadway classifications, using an incomplete factorial design. This was the most comprehensive study in work zone speed reduction found in the literature to date. In this study, the authors found the most effective speed reduction methods was flagging and enforcement, while Changeable Message Signs (CMS) and lane width reduction were also found to be effective. Due to the incomplete factorial design, not all of the strategies were implemented at all work zone sites so the comparisons among some of the strategies could be biased or lack confidence. Nonetheless, among the enforcement strategies, police traffic controller was found to be the most effective, and a circulating patrol car was found to be clearly the least effective, which was abandoned after only one site for its "poor performance on the two-lane highway and likely even less effectiveness on divided, multilane roadways with limited access

TABLE 2.4
Summary of Studies on Effect of Work Zone Police Enforcement

Researcher	Year	Roadway Type	Enforcement Strategy	Average Speed Reduction
Graham et al.	1977	Rural freeway	Circulating	3 mph
Richards et al. (*37*)	1984	Rural freeway	Stationary	5 to 9 mph
		Urban freeway	Stationary	3 to 6 mph
		Urban arterial	Stationary	12 mph
			Traffic controller	13 mph
		Rural 2-lane highway	Circulating	2 to 3 mph
			Stationary	7 mph
			Traffic controller	9 to 14 mph
Noel et al. (*38*)	1987	Rural freeway	Stationary	6 to 8 mph
			Traffic controller	3 mph
Kackels and Brannon	1988	Rural freeway	Stationary	13 mph
Benekohal et al. (*20*)	1992	Rural freeway	Circulating	4 to 5 mph
McCoy and Bonneson (*46*)	1993	Urban arterial	Stationary	5 mph
MnDOT	1999	Rural freeway	Stationary	8 mph
		Urban freeway	Stationary	8 mph
		Urban arterial	Stationary	9 mph
Wasson et al. (*34*)	2010	Rural freeway	Multiple	2 to 5 mph
Zech et al. (*21*)	2005	Urban freeway	Stationary with rumble strip	3 to 4.5 mph
Medina et al.	2009	Rural freeway	Stationary with speed display trailer	-2.1 to 2.7 mph*

Source: (*18*).
*Negative sign indicates speed increase.

points." While stationary police enforcement with emergency lights and radar off were used in almost every site and were found reasonably effective, stationary police enforcement with emergency lights or radar on were tested at only one site and was found to be more effective than stationary police enforcement with emergency lights and radar off at that same site, but less effective than the overall average. The authors noted that police officers are rather reluctant to perform traffic controller duties on a freeway for concerns about their personal safety and believing it likely would be less effectiveness in that environment.

Richards et al. also noticed that the same speed reduction strategy could have very different effectiveness across sites and even for sites that fall into the same roadway classification. They further speculated that some site specific characteristics (e.g., alignment, distance to urban center, truck percentage) may have contributed to such differences, but lacked theoretical proof of their speculations due to the limited number of work zones.

Another interesting finding from this study was that, based on the speed profile (speeds measured from different stations) from one site (urban arterial), it appeared that while police enforcement and flagging had a greater initial and overall effect, it deteriorated quickly while the speed reduction caused by the CMS and lane width reduction were more consistent throughout the length of the work zone. However, such information was available from only one site, and the downstream speed information was measured at only one station 1/3 to 1/2 mile downstream of the treatment.

To sum up, the Richards et al. study (*37*) evaluated the effectiveness of various speed reduction strategies with an incomplete factorial design and remains to be the most comprehensive study on this subject to date. The findings from this study, though from almost three decades ago, provided important insight and guidance to the design and implementation of this current study.

In the Noel (*38*) study, four different strategies were implemented in freeway work zones, each for a consecutive 10 to 15-day period. This study was conducted in 1987, and three of the four strategies used were variants of flaggers, which included MUTCD flagging, innovative flagging, and police traffic controller. The other strategy used was stationary police enforcement with emergency lights and radar on. This study was carried out in four work zone sites located on I-495, and all were six-lane freeway sections in a suburban area. Each site had lane closure of one lane each direction and two lanes each direction. One critical flaw of this study design was that each strategy was carried out at a different site, which will unavoidably confound the site-specific effects with the effectiveness of the enforcement strategy. The other flaw identified (also by the authors) was that the upstream speed was used to adjust for the net speed change when lane closure existed, which could have led to biased results, especially in situations when three lanes were reduced to one lane for each direction. Nonetheless, the authors identified that the two strategies involving police presence had a consistently good effect, with a 4 mph reduction in the early implementation period and 6.4 mph (two lanes closed) and 8.4 mph (one lane closed) reductions in the later period. Flaggers had varying effects for different situations and time periods and ranged from a 6.7 mph increase to a 6.7 mph decrease in speed.

In the previously mentioned Benekohal study (*20*), the authors specifically studied the effect of circulating patrol, using a marked police car patrolling a 3.5-mile work zone along a rural freeway section. The authors used a free flow vehicle only for data analysis and eliminated all other affecting factors (e.g., presence of flagman, speed limit flash lights off, etc.). Also, the point speed was measured from three stations, with the first station upstream of the work zone (two lanes) and the second and third stations within the work zone (one lane open). The differences in speed change from the first station to the second and third stations were measured between the treatment day (with police enforcement) and the control day (without police enforcement). They found that, with or without the police enforcement, the speed at station 3 (end of the work zone) was consistently higher than the speed at station 2 (near the beginning) with all vehicle traveling above the posted speed limit. With police enforcement, the net speed reduction of cars was around 4–4.5 mph and for trucks was 5 mph at station 2 and 4.3 mph at station 3. The results show that the effect of police enforcement is slightly higher for trucks than for cars (also a temporal residual effect for trucks), and that the speeding at the end of work zones is more severe than at the beginning.

The also previously mentioned Wasson study (*34*) carried out a saturated police enforcement plan, which the authors referred as a "blitz." Twelve Indiana State Police officers with vehicles that included marked cars, unmarked cars, unmarked Ford Mustangs, motorcycles, and commercial enforcement units, carried out enforcement along a 12-mile long rural freeway work zone. The speed data were collected using Bluetooth sensors; and with 13 stations, the travel times could be collected for 12 roads sections, which then were used to calculate speed. One issue with the Bluetooth sensors was that only a sample of the entire vehicle fleet could be collected, and this sample was suspected as being self-selected. In this study, 11% of the entire vehicle fleet was collected. The data analysis shows that, with this very intense police enforcement, the speed reduction for different directions and different work zone sections ranged from 2 to 5 mph, and a considerable number of vehicles were found to be traveling above the posted speed limit. This study therefore might suggest that the marginal effect of additional police enforcement in one single work zone is not significant.

In the Zech study (*21*), the primary purpose was to study the effect of two different rumble strips in speed reduction in work zones, but police enforcement was also used in this study. The police enforcement strategy was only applied in one work zone on I-990 in Buffalo, New York. While the rumble strips used at this site showed no statistically significant reduction both in speed and variance in speed, the combination of police presence and rumble strips induced a speed reduction of 3 to 4.5 mph and also reduced the variance of speed by around 25%. It could be concluded that this reduction in both speed and variance was attributable mainly to the police presence.

In the Medina study (*23*), again the primary objective was not to study the effect of police enforcement. The authors conducted other studies on the effect of the photo speed enforcement strategies, but in this study they focused on the downstream effect of such strategies and compared them with the downstream effect of police enforcement. This study was discussed in the Lasting Effect section, thus it is not repeated here.

Immediate effect (Alternative Enforcement Strategies). In recent years, a lot of studies have been carried out utilizing alternative strategies for work zone speed enforcement. Such alternative strategies can be implemented without police enforcement due to their relatively low cost and easy deployment, which also eliminates the exposure of police officers in the dangerous highway environment. However, due to legislation in Indiana, photo speed enforcement is illegal in Indiana, thus the effectiveness of camera-based speed enforcement strategies will only be briefly discussed.

In the Richards et al. study (*37*), as previously mentioned, CMS was tested as one of the speed reduction techniques. While the effect varied across roadway classifications and also individual sites, the effect was found to range from no effect to a 5 mph reduction.

Benekohal et al. (*30*) carried out a study to evaluating the effectiveness of Speed Photo Enforcement (SPE). SPE was implemented in a work zone with a 55 mph speed limit, and point speeds were measured at two locations (one immediately downstream of the treatment, the other 1.5 miles downstream). Two sets of speeds were used for analysis, one set for free-flow vehicles only and the other set consisted of systematically drawn samples (every fifth vehicle). The authors found that even the free-flow vehicles showed a consistently higher speed of around 2 mph compared to the sample vehicle, and the speed reduction was similar in both samples. At the treatment location, the speed reduction ranged from 3.2 to 6.4 mph for free-flow vehicle and 4.1 to 7.3 for the sampled vehicles; and the percent of speeding was reduced from 39.8% to 8.3% for free-flow traffic and 27.7% to 6.3% for the sampled vehicles. At the downstream location, however, the speed reduction was only significant for trucks and ranged from 1.7 to 2.5 mph.

Bloch (*22*) compared the effect of two alternative strategies, namely, Photo-Radar and Speed Display Board. The author found that both strategies, along with supplementing the Speed Display Board with intermittent police enforcement, were significantly effective in reducing speed. With two weeks of control data and two weeks of treatment data, the authors found that all three strategies reduced speed by a little more than 5 mph at the treatment location (5.2 mph for Photo-Radar, 5.8 for Speed Display Board, and 6.1 mph for Speed Display Board with supplemental police enforcement), while the difference at the downstream location was significantly different, which was discussed in the Lasting Effect section. Of special notice for this study, these treatments were carried out in non-construction sites that were located on city streets, as compared to the other studies which were all carried out in work zones located on freeways or highways.

Pesti and McCoy (*31*) evaluated the long-term effect of speed monitoring displays. Three speed monitoring displays were deployed along a 2.7 mile rural freeway work zone for five weeks. This section of road was between two relatively long head-to-head sections (crossover lane closure), where excessive speed would be expected. The data analysis showed that the mean speed was reduced by 3 to 4 mph during the treatment period while the 85 percentile speed was reduced by as much as 7 mph. Speed limit compliance was found to increase from about 20% to about 40%.

In another study by Brewer et al. (*33*), the effectiveness in speed reduction of three alternative strategies was evaluated in Texas. Evaluated in this study were a speed display trailer, a variable message sign with radar, and an orange-bordered speed limit sign. A before and after study was conducted to evaluate their effectiveness. The analysis showed that the orange-ordered speed limit sign had a minimal effect on speed reduction while the other two methods were statistically significant in that they reduced the 85th percentile speed, but by only 2 mph.

Finally, Thomas et al. (*32*) conducted a review of non-U.S. studies regarding the safety benefit of mobile Automated Speed Enforcement. Thirteen suitable studies were reviewed in detail, and the conclusion was that a 20% to 25% reduction in injury crashes was possible by Automated Speed Enforcement programs.

2.3 Literature Study Summary

For both major components in this current project, the body of literature provided invaluable knowledge and guidance but showed some limitations.

Regarding work zone crash modeling, although many studies could be identified, very few included detailed work zone features variables while maintaining a reasonable sample size at the same time, suggesting the difficulty in collecting work zone-related information. Also, no prior studies directly included police enforcement activities in the modeling at the road segment level.

Limitations aside, the current body of literature does suggest that:

- Crash rates during a construction period tend to be considerably higher than before the construction period.
- Crash severity is also likely to increase during the construction period, but only few studies could show their statistical significance.

- Work zone characteristics such as lane closure, crossover, and high construction intensity were found to increase the crash rate.
- Traffic characteristics and driver behavior have been identified as contributing factors of safety in work zones.
- Data availability has been identified as a major obstacle for better understanding of work zone crashes.

The literature on the effectiveness of police enforcement is also quite limited. The lack of systematic comparison of different strategies is the most serious void. The only experiment that aimed to compare the effectiveness of police enforcement took place in 1985. Nonetheless, the literature study on this topic provided the following guidance useful for designing the experiments in this study and for interpreting the obtained results:

- The effectiveness of various work zone enforcement strategies have been identified; and the strategy that was the most effective, most consistent, and easy to implement is stationary police enforcement.
- Many techniques without police presence were found effective, either supplemental to police enforcement or used alone.
- The same enforcement strategy may have different effectiveness at different sites due to local factors.
- The residual effect of police enforcement, both spatial and temporal, is short-lived in work zones.

With the knowledge learned, the Purdue Research Team proceeded to data collection and analysis. Specific attention was paid to the limitations of the current body of literature, and efforts were made to overcome these limitations and thereby contribute to the body of knowledge.

3. IDENTIFICATION OF HIGH RISK WORK ZONES

3.1 Data Needs and Collection

A notable limitation identified from the work zone crash modeling literature is that data availability is a major issue. Few models found in the literature included detailed work zone feature variables and had a substantial sample size at the same time. Thus, great emphasis was put on data collection towards the work zone modeling.

3.1.1 Data Needs Assessment

The data needs assessment was carried out in a very early stage of this project. Various types of data were identified as necessary by the Purdue Research Team in order to carry out the analysis. This information includes the roadway characteristics prior to road construction, work zone features and traffic management information, traffic volume, presence of police enforcement, and of course crash history, among others.

The Purdue Research Team identified the data needs, and INDOT helped identify and retrieve the data. Also, as the analysis proceeded, more data needs were identified, and the collaboration between the Purdue Research Team and INDOT was very successful. In the end, four major components were included: 1) the GIS-based road characteristics dataset maintained by Center for Road Safety (CRS) at Purdue University; 2) a work zone feature dataset survey by the Purdue Research Team with help from INDOT; 3) the crash database maintained by CRS; and 4) the ISP work zone activity log provided by INDOT.

The following sections will describe each component in detail.

3.1.2 GIS Road Inventory Dataset

The Center for Road Safety maintains a GIS-based road inventory datasets (for all roads in Indiana), which include information such as jurisdiction; urban/rural; functional class; number of lanes; pavement type and condition; width of the lanes, shoulders and median; type of median and shoulder; traffic volume; presence of curb or parking lane.

Other than provide road characteristics information prior to construction, this GIS Road Inventory dataset also serves as a base to link all data from different sources together.

3.1.3 INDOT PE Survey

The studied literature indicated the difficulty in assembling a comprehensive and representative database; and authors were forced to use sparse data (i.e., some authors had a very limited number of work zones while others had to conduct their studies without work zone feature variables). In spite of the recent effort to overcome the data limitation in Wisconsin (*13*), Wisconsin data does not include work zones without lane closures.

To overcome the data limitation, our research team made an extensive effort to acquire rather detailed data from a considerable number of work zones. As decided during the first SAC meeting, an INDOT Project Engineer survey was carried out to retrieve the work zone characteristics. INDOT provided a dataset with 2009 and 2010 Indiana work zones on state-maintained roads (including both freeways and non-freeways). Available in the dataset are the project level information, including jurisdiction, location, total award, and brief description of the project. More detailed information like the cross-section elements and traffic management components were not included. In order to obtain this vital information, a survey was designed and conducted among the INDOT project engineers who managed these projects. Start and end dates, cross-section design (number of lane open, lane shift, etc.), traffic management details (use of barrier, detour sign, etc.), and presence of police enforcement were collected for each phase of the construction period. Detailed instructions and a sample form were provided with the survey form. Jim Poturalski from INDOT helped distribute and collect this survey. A sample survey form is shown in Appendix 1.

Considering the scope of this project, not all highway work zones were appropriate for inclusion in this modeling analysis. Some "point work zones," (e.g., intersection modification, overhead bridge painting) or projects having very minor impact on traffic (e.g., guardrail installation, turf maintenance) along with projects termed "various locations," were not selected to be included in the survey. With the above criteria, 189 projects were selected to be included in the survey.

Out of 189 questionnaires sent out, 78 were returned; six lacked important information and were excluded from the analysis. The final dataset included 72 work zones, but 2 of them also were missing some variables. Eventually, the assembled dataset contained 70 complete observations and two incomplete observations. To check whether these 72 work zones were uniformly distributed across Indiana, their starting and ending points were marked in Google Earth. Figure 3.1 presents these locations. Even though there seem to be clusters of work zones in certain areas, probably due to more work zones or a higher return rate there, the overall distribution of the work zones is satisfactory.

The collected work zone survey data was coded in the ArcGIS database and then integrated with the Indiana Road Inventory (IRI).

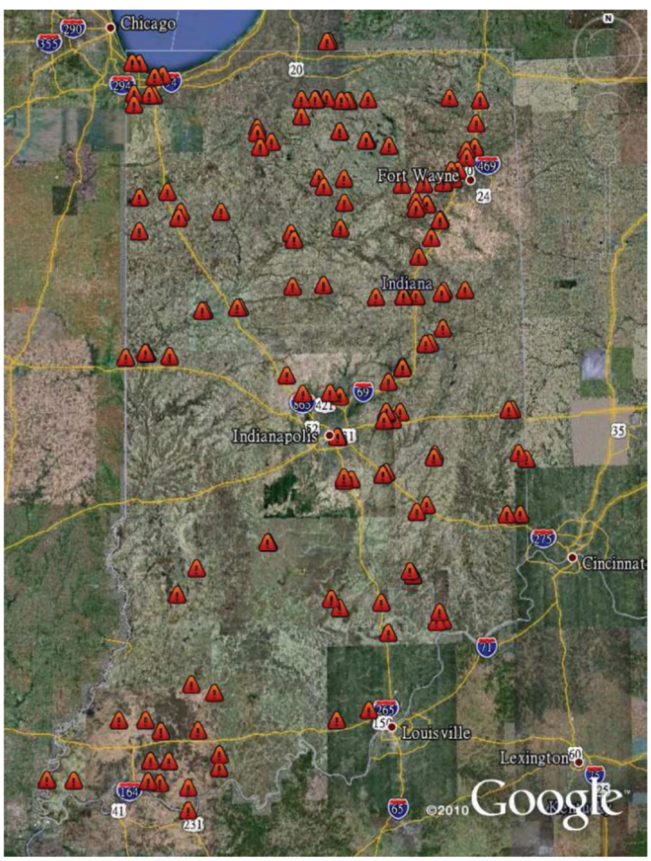

Figure 3.1 Distribution of work zones in Indiana. (Image from Google Earth.)

3.1.4 Police Enforcement Information

As this current project concerns police enforcement in highway work zones, the police enforcement information in the past work zones was of great interest. The police enforcement information was sought from two sources: the ISP enforcement activity log and the INDOT project engineer's reported enforcement.

As INDOT has been funding ISP for work zone police enforcement, police enforcement activity log data were obtained from ISP and were available for analysis by the Purdue Research Team. A host of variables were available from this activity log. Among the available enforcement data, the number of enforcement hours and miles driven were included in the dataset for modeling. Unfortunately, out of the 72 work zones, only nine had been funded for special police enforcement by INDOT. This sample size was considered too small and possibly incapable of providing enough perspective for the analysis.

Fortunately, the police enforcement information also was collected in the work zone survey from the project engineers. For each distinctive construction phase, the project engineers were to choose from several types of police enforcement, along with no enforcement observed. Project engineers were to choose from conspicuous and ticketing, conspicuous and non-ticketing, and inconspicuous and ticketing enforcement types. Since this variable was collected from the survey, it was available for all single work zones in our sample. Out of the 72 work zones, 24 project engineers reported there was police enforcement observed in the work zone.

The advantage of this project engineer-reported enforcement variable was that not only was it more representative than the ISP activity log data, it was more complete as well because along with the INDOT-contracted activities, the other enforcement activities conducted by ISP and by local enforcement agencies were reported. However, the downside of this variable was also obvious. First, only one variable cannot represent the frequency or intensity of the enforcement in the work zone; and second, the reliability of this "reported" variable cannot match that of the enforcement activity log data directly obtained from ISP. Thus, police enforcement information from both sources was included in the final database and used for analysis, which is shown in the next section.

3.1.5 Work Zone Characteristics and Crash Data Integration

The collected work zone survey data were coded in the ArcGIS database and linked with the Indiana Road Inventory (IRI) data maintained by the Program Development Division of INDOT.

The work zones were first identified on Google Map based on the description of the project. All work zones were identified prior to being sent to INDOT project engineers. Some work zones did not have specific enough description about their locations and thus were rejected for the survey. Then, the identified work zones were located on a GIS map and geo-coded and integrated with the IRI data.

An ArcGIS-based crash database is available in the Center for Road Safety, which includes information about crash type, time and location, vehicle, and people involved. Crash records from 2008–2010 were used for this study. Vehicle and personal information was first aggregated into the crash level. Then, the crash location and date were used to select crashes that happened in one of the 72 work zones, which then were assigned to the corresponding work zone and construction phase. Crashes that happened prior to the construction project or during a non-construction period were all marked as "non-construction period." There were 8,647 crashes initially selected, and 1,757 were identified as work zone crashes (happened during the construction period) and 6,890 non-work zone crashes (happened during non-construction period).

To account for the monthly changes in enforcement, weather, traffic, and construction phases, the modeling was applied to monthly observations. The AADT monthly adjustment factors were used to convert the AADTs into month-specific ADTs. To properly represent the duration of construction activities in monthly observations, the duration was measured in days. Splitting the entire period with data into months produced 2,722 monthly observations with 547 work zone observations and 2,175 non-work zone observations. The obtained data are described and summarized in Table 3.1 and Table 3.2. Due to the large number of variables, only the primary variables are included in these tables.

3.1.6 Work Zone Crash Database Summary

Assembling the dataset was the first step necessary in order to develop meaningful and useful statistical models. The survey of INDOT project engineers to obtain detailed work zone information for the number of work zones was unprecedented and not found in the studied literature. The resulting dataset represented a good balance between the scope and detail. In addition, the dataset included unique police enforcement data obtained from ISP and from INDOT project engineers.

3.2 Work Zone Crash Frequency Modeling

In the previous step, the work zone characteristics and crash data process, a database was assembled for the statistical analysis and modeling. This database includes information from the survey of INDOT project engineers, the Indiana crash database, the

TABLE 3.1
Descriptive Statistics for Continuous Variables

Variable	Description	Mean	Std Dev	Minimum	Maximum
COLLECT	Fraction of collectors	0.1447	0.3121	0.0000	1.0000
TURN	Fraction with turning lane	0.1982	0.3051	0.0000	1.0000
PARK	Fraction with parking lane	0.0266	0.0804	0.0000	0.4344
PRTACCESS	Fraction with partial access control	0.0483	0.1728	0.0000	1.0000
ACCESS	Fraction with full access control	0.2462	0.4199	0.0000	1.0000
URBAN	Urban fraction	0.4176	0.4143	0.0000	1.0000
AADTadj	Adjusted AADT (in thousands)	20.1546	24.9720	0.6961	124.9070
LOGLEN	Logarithm of length (mile)	1.2822	1.1427	-1.3189	3.2630
TOTVOLUME	AADT by number of days (in thousands)	481.2429	647.3989	5.7660	3747.2100
LOGVOL	Logarithm of total volume	5.5073	1.2068	1.7520	8.2288
LANE	Average number of lanes	3.4083	1.6409	2.0000	7.0000
LSW	Average left shoulder width	3.9805	3.2059	0.0000	16.4444
NBW	Average traveled way width	27.1782	6.3563	18.0000	48.0000
MW	Average median width	16.6806	24.3351	0.0000	80.0960
SW	Average shoulder width	5.9021	3.8650	0.0000	13.0000
RWW	Average ROW width	139.9544	97.3268	37.7982	412.8000
FR	Average friction	4.8624	3.1742	0.0000	13.3040
SI	Average roughness	36.7475	7.1685	4.7368	50.0000
SR	Average condition rating	35.5858	5.4566	25.4745	45.0000
DURATION	Duration of project	310.0219	200.8586	16.0000	699.0000
DAYS	Number of days for the phase	24.7221	8.2486	2.0000	30.0000
LENGTH	Work zone length (mile)	6.0196	5.4323	0.2674	26.1266
AWARD	Total project award	15331387	24454988	275765	97400000
INTENSITY	Work intensity in \$1,000/(day $\times$ mi)	12.7699	15.7671	0.0000	59.8273
EFCMILE	Enforcement miles per day (1000 miles)	0.0210	0.1316	0.0000	2.1980
EFCHOUR	Enforcement hours per day	1.6122	10.2468	0.0000	187.2500
LANEDROP	Number of travel lanes dropped	1.26	1.43	-3.00	4.00
LANEWIDTH	Average travel lane width	11.4601	1.8829	9.0000	17.0465

TABLE 3.2
Descriptive Statistics for Dummy Variables

Variable	Description	N	0	1	Percent 1
DETOUR	With detour sign	547	348	199	36.380%
NEW	With traffic on new pavement	547	112	435	79.525%
BARRIER	With barrier	547	345	202	36.929%
SHOULDER	With traffic on shoulder	547	431	116	21.207%
SHIFT	With lane shift	547	238	309	56.490%
SPLIT	With lane split	547	489	58	10.603%
ENFORCE_A	With conspicuous and ticketing enforcement	547	287	260	47.532%
ENFORCE_B	With conspicuous and non-ticketing enforcement	547	524	23	4.205%
ENFORCE_C	With inconspicuous and ticketing enforcement	547	541	6	1.097%
TICKETING	With ENFORCE_A or ENFORCE_C	547	281	266	48.629%
ENFORCE	With any observed police enforcement	547	258	289	52.834%
FR_LW	Average friction lower or equals to 4	547	309	238	43.510%
FR_HW	Average friction greater than 8	547	465	82	14.991%
SI_LW	Average roughness lower or equals to 30	547	446	101	18.464%
SI_HW	Average roughness greater than 40	547	378	169	30.896%
SR_LW	Average condition rating lower or equals to 30	547	410	137	25.046%
SR_HW	Average condition rating greater than 40	547	405	142	25.960%
MAYJUL	Working phase from May to July	547	382	165	30.165%
NOVDEC	Working phase from November to December	547	464	83	15.174%
LWINT	Working intensity lower or equals to $10,000/(day × mi)	547	243	304	55.576%
HWINT	Working intensity greater than $35,000/(day × mi)	547	478	69	12.614%

Indiana Roadway Inventory data, and the ISP work zone enforcement activities data. This dataset represents a good balance between scope and detail. In addition, the dataset included unique police enforcement data obtained from ISP and INDOT project engineers. In the first phase of data analysis, this dataset was used to model crash frequency in the INDOT-funded work zones.

To suit different needs, three different models were estimated.

The first model is a historical work zone crash model, based on monthly observations. The purpose of this model is to use all of the available variables that fit a model as good as possible. This is similar to most of the models found in the literature.

The second model is a historical work zone crash model, based on work zone level observations. The purpose of this model is to provide INDOT a more accessible alternative while maintaining reasonable prediction power.

The final model is a work zone crash model used for predicting, based on monthly observations. The difference between this model and the first one is, for predicting purpose, some variables will not be available, and thus need to be removed. This model was ultimately chosen to be adopted for the final programming tool developed for INDOT.

3.2.1 Methodology

In modeling crash frequency, due to the nonnegative integer nature of the data, Poisson or Negative Binomial regression is the predominant methods. Poisson regression assumes the mean rate λ_i to be a function of the predictors, and it restricts the variance to be equal to the mean (*39,40*):

$$E[y_i] = \lambda_i = EXP[\beta x_i]$$

$$VAR[y_i] = E[y_i]$$

The Negative Binomial regression relaxes the restriction by adding a Gamma-distributed dispersion term ε_i, as expressed as:

$$E[y_i] = \lambda_i = EXP[\beta x_i + \varepsilon_i]$$

$$VAR[y_i] = E[y_i][1 + \alpha E[y_i]] = E[y_i] + \alpha E[y_i]^2$$

where α is referred to as dispersion parameter. This added dispersion term gives the Negative Binomial models the ability to handle over-dispersion in the data. However, sometimes an excessively large amount of zeros beyond the capability of Negative Binomial models could exist in the data. Zero-Inflated Poisson and Negative Binomial regressions account for this issue by assuming a dual state data generating process. The zero state and non-zero state were first distinguished by a binary process, followed by a regular Poisson or Negative regression for the non-zero state. Zero-Inflated models have seen popularity for their ability to handle over-dispersed data (*39–40*). However, there has been a debate on the use of Zero-Inflated Count models in crash frequency modeling; Lord et al. (*41–42*) argued that the dual state data generating process in Zero-Inflated models would be hard to justify and interpret in the application of traffic safety. More recently, Random Parameter Count models have risen due to their desirable statistical properties. Rather than assuming that the parameters hold constant for all observations, Random Parameter models relax this assumption and allow the parameters to follow a certain distribution, thus reducing bias and making them capable of estimating variances more effectively (*40*). However, the Random Parameter models are computationally cumbersome and often hard to estimate. Also, the statistical inferences and interpretation of the Random Parameter models can be less straightforward, especially when our study focuses on implementation. As previously mentioned, our database was restructured into a month by month format, with each observation representing one month at a work zone. This reorganization required a structure similar to that of panel data. If this dataset were modeled directly without accounting for the unobserved correlation within each work zone, the assumption of independence would be seriously violated. Fixed effect and random effect models could be used to account for this correlation; however, while a series of work zone characteristics variables are available in the dataset, the introduction of fixed effect could very likely overwhelm all of the work zone characteristics. Thus, random effect was introduced to the model to account for the shared unobserved correlation within work zones. For the Random Effect Negative Binomial model, the expectation of the dependent variable could be expressed as:

$$\lambda_{ij} = EXP[\beta x_{ij}]\,EXP[\varepsilon_{ij}]\,EXP[\eta_j]$$

Where the subscript j is the group variable (work zone in this case), and η_j is the random effect for the jth group.

Finally, as most researchers found that crash frequency possesses a somehow linear relationship with "exposure" variables like ADT and length of the section, such exposure variables were used in their Logarithm forms. Similar to Venugopal and Tarko (*9*), in the final model, the work zone length and the total traffic volume were used as exposure variables, as shown below:

$$\lambda_{ij} = Length^{\beta}\ TotVol^{\beta}\ EXP[\beta x_{ij}]\,EXP[\varepsilon_{ij}]\,EXP[\eta_j]$$

The frequency dataset was first partitioned into two subsets, one for construction periods and the other for non-construction periods. Random Effect Negative Binomial models were estimated for each dataset to identify the most significant predicting variables for each subset. The modeling result for the non-construction periods is not the concern of this study and therefore is not presented here.

3.2.2 Monthly Observation Model

In this assembled dataset, each data point is a disaggregated observation for each work zone, in each month. This dataset then enables the estimation of a monthly observation model, with all the detailed information at the monthly level.

The model was estimated in SAS using the GLIMMIX procedure (*43*). The GLIMMIX procedure is capable of handling general linear regression with the presence of correlation or inconstant variation. By incorporating random effects, this procedure is capable of producing subject-specific (conditional) and population-averaged (marginal) inferences. Pseudo-Likelihood techniques were used to estimate the model with random effects. Statistical inferences were performed based on a Wald-type test for the fixed effects and based on likelihood ratio tests for the covariance parameters.

As required by SAS, the dataset used the categorical variables, and the fixed effects were specified in SAS codes. For this application, Negative Binomial had to be specified in the model statement. Also, the Random statement was used to incorporate the random effects at the work zone level. In this model, we let the intercept vary at the work zone level. The option solution was used to display the parameter estimation for the fixed effects.

The fixed effects were selected using 90% confidence intervals, and correlation among these predicting variables was checked. Actions were taken if moderate to severe correlations between variables were identified. The parameter estimations of the final model are presented in Table 3.3 and Table 3.4.

We can see from Table 3.3 that the random effect is significant in this case, with an estimate of 0.1639 and an asymptotic standard error of 0.0529. The GLIMMIX procedure, however, only fit the normally distributed random effect. Since there is no prior knowledge about the distribution of this random effect, normal distribution was considered appropriate. The significant random effect suggested that there were shared unobserved correlations at the work zone level, and the use of the Random Effect model was necessary to produce reliable modeling result.

The Scale in the Covariance Parameter Estimates is the over-dispersion parameter α, for the Negative Binomial model. The estimate for the over-dispersion parameter is 0.0629 and the asymptotic standard error is 0.0227, which suggests that the over-dispersion, although small, is significant in this model and the use of the Negative Binomial model was justified.

The description of the fixed effect variables can be found in Table 3.4. The work zone length, work phase duration, and adjusted total traffic volume were treated as exposure variables, and their logarithm forms were used in the model. The estimate for the duration of the working phase and the adjusted ADT were not

TABLE 3.3
Covariance Parameter Estimates

Cov Parm	Subject	Estimate	Std Error
Intercept	Contract	0.1639	0.0529
Scale		0.0629	0.0227

statistically different from each other so they were combined (total volume) to add parsimony to the model.

The parameter for the work zone length was close to 1, which suggests that the crash frequency is almost linearly dependent on the work zone length. The Total Volume (VOL) was also a strong factor of the crash frequency. Unlike the work zone length, it was smaller than 1 at the nearly 95% confidence level ($p = 0.0512$), which means that the rate at which the crash frequency increases with growing traffic volume becomes smaller if the VOL becomes high. It may also mean that longer lasting work zones with higher traffic volumes exhibit lower crash rates (per unit duration or unit volume) than shorter lasting or less busy work zones. This result confirms the findings by Venugopal and Tarko (*9*).

Also presented in Table 3.4 are the marginal effects for continuous predictors and pseudo-marginal effects for binary predictors. They were calculated as exponents of the corresponding model coefficients. URBAN, ACCESS, PARK, COLLECT, and CSRLOW are fractions indicating the portion of the work zone section that is in urban areas, has full access control, includes a parking lane in the before work zone conditions, is a collector road, and the concrete pavement has low condition ratings before the work zone period, respectively. LSW and RWW are continuous variables, and the other variables are binary. The variable URBAN had a strong increasing effect on the crash frequency, which could be due to frequent intersections and ramps, strong heterogeneity in the traffic flow conditions, and restricted geometric design in urban areas. The effect of ACCESS was less pronounced then URBAN, but its coefficient suggested that highway work zones on full access controlled highways experience more crashes. This effect might be due to generally higher speeds on these roads while the geometry conditions are downgraded during the construction period. Work zones on collector roads (COLLECT = 1) experienced more crashes than other roads, which was most likely due to the lower geometry standard of these roads that may affect the work zone conditions. The model parameter associated with the PARK variable indicates that the availability of additional paved area provided by a parking lane greatly reduced the crash frequency. Twenty-two percent of the work zones had the non-zero PARK variable, which varied between zero and 43% across all work zones.

CSRLOW is the interaction between the concrete pavement variable (fraction of the work zone length) and the binary indicator of a low condition rating before a work zone period. Thus, this variable may be indicative of certain work activities and work zone conditions associated with these pre-construction conditions. The CSRLOW-implied pre-construction conditions are associated with more frequent crashes during the construction period.

Both of the continuous variables, LSW and RWW, had negative coefficients, indicating that wide shoulders and wide rights of way are associated with a lower frequency of work zone crashes. Although the coefficients are fairly small, they express the effect per foot, and thus the average impact of these variables was considerable. This finding concurs with the positive effect on safety of the additional width added by the presence of a parking lane in pre-construction conditions.

NOVDEC and MAYJUL are binary variables. Adjacent months that had similar effects on safety were grouped together, and NOVDEC represents November and December (late fall), while MAYJUL represents the three months of May, June, and July

TABLE 3.4
Fixed Effect Parameter Estimates and Marginal Effects

Variable	Variable Description	Estimate	t Value	Effect
Intercept	Constant	-5.8891	-13.56	N/A
LOGLEN	Logarithm of the work segment length (mi)	0.9467	10.1	N/A
LOGVOL	Logarithm of the total volume (in thousands) of through traffic during the observation period	0.8851	12.58	N/A
URBAN[a]	Fraction of the work zone length in an urban area	1.3441	4.89	3.8347
ACCESS[a]	Fraction of the work zone length on a road facility with full access control	0.5748	2.03	1.7768
PARK[a]	Fraction of the work zone length with a parking lane prior to the construction period	-2.2084	-2.14	0.1099
COLLECT[a]	Fraction of the work zone length categorized as collector road	0.4007	1.58	1.4929
LSW[b]	Average width of the left shoulder (ft) prior to the construction period	-0.0526	-1.99	0.9488
RWW[b]	Average width of the right of way (ft) prior to the construction period	-0.0047	-3.79	0.9953
SHIFT	Indicator variable for existence of lane shift during the construction phase	0.1933	1.85	1.2132
SPLIT	Indicator variable for existence of lane split during the construction phase	0.2886	1.87	1.3346
NOVDEC	Indicator variable if the observation period is in November or December	0.2170	2.54	1.2423
MAYJUL	Indicator variable if the observation period is in May, June or July	0.1815	2.7	1.199
CSRLOW[a]	Indicator variable for concrete pavement with low condition rating (<30)	0.7406	1.91	2.0972
LWINT	Indicator variable for low work intensity (construction cost $<$ \$10,000/(day $\times$ mi))	0.4922	2.24	1.6359
HWINT	Indicator variable for high work intensity (construction cost $>$ \$35,000/(day $\times$ mi))	0.9489	3.06	2.5829
ENFORCE	Indicator variable for police enforcement observed by project engineer	-0.5360	-3.51	0.5851

[a]Fraction—the effect is per unit change (here per 1); thus the actual effect is smaller than the marginal effect.
[b]Continuous variables—the effect is per 1 unit change (foot); thus the actual effect is typically higher than the marginal effect.

(late spring and early summer). The frequency of crashes was 24% higher in the NOVDEC period and 20% higher in the MAYJUL period than in the remaining part of the year. These effects may be attributed to holiday traffic and poor weather in the late fall season, and increased vacation traffic and more young drivers in May, June, and July.

The remaining variables were important work zone-related variables. SHIFT and SPLIT correspond to lane shifts and splits in work zones. Both of them seemed to increase the work zone crash frequency. A lane split had a more profound effect than the lane shift. HWINT and LHINT are binary variables representing the intensity of construction work measured in the average project cost per mile and day. High work intensity (HWINT=1) corresponds to projects with more than \$35,000 spent per mile per day, while low work intensity (LWINT=1) corresponds to projects with less than or equal to \$10,000 spent per mile per day. High work intensity and low work intensity construction zones experienced significantly higher crash frequency than moderate work intensity zones.

Finally, the ENFORCE variable indicates the considerable presence of police enforcement during the work zone period. The results indicate that a 41% reduction in the crash frequency could be attributed to the police enforcement. No significant difference between the enforcement types (conspicuous/not conspicuous, with ticketing/without ticketing) could be detected.

The INDOT-funded enforcement, represented through enforcement hours and miles driven, were found to be insignificant. Two explanations are possible: 1) only nine of the 72 work zones utilized INDOT-funded enforcement; and 2) as pointed out by Lord and Mannering (*44*), some variables in regression models may exhibit an endogeneity problem. The INDOT-funded enforcement targeted long-term work zones with anticipated safety problems. In some cases, this enforcement could be a direct response to an observed safety issue in these work zones. This situation might induce endogeneity to the model and make this effect undetectable through a cross-sectional analysis. On the other hand, the police enforcement reported by project engineers was executed by local and state law enforcement agencies. These police enforcement activities are supposed to be less correlated with, if not independent from, the past crash experience in work zones due to the temporary nature of work zones.

3.2.3 Work Zone Level Aggregated Model

The model estimated previously was based on monthly observation, which is more accurate since it takes into account the monthly variations of AADT, some monthly trends, and temporal changes that could take place for work zone features and enforcement. However, this model required data from various sources and large amounts of data processing to integrate the dataset. To simplify implementation of the model, a simplified model was estimated using each work zone as observation. This model was expected to have slightly worse predicting power compared to the monthly-based model. However, considering the amount of additional effort needed to estimate the monthly observation model, the use of the simplified model was justified and would be more realistic in most occasions. The model was also estimated in SAS using the GLIMMIX procedure, but since there are no repeated observations for each work zone, there is no unobserved shared correlation. Thus, the model was estimated as a Negative Binomial Model, and the explanatory variables and their coefficients are presented in Table 3.5.

Most of the information was obtained from the Indiana Roadway Inventory database and from the work zone contract documents, which was readily accessible to INDOT. In this model, the traffic volume was a weighted average of the monthly ADT over the entire period of the construction, calculated with the AADT adjustment factors and the work zone duration.

All of the remaining coefficients maintained their sign in the simplified model, with the magnitudes of some changing, but not significantly. Two observations worth noting were the exposure variables and the effect of police enforcement.

In the previous monthly observation model, the coefficients for the exposure variables were both slightly

TABLE 3.5
Variables for Implementation of the Interim Prioritization Tool

Variable	Description	Coefficient
Intercept		-5.9854
LOGLEN	Logarithm of the work segment length (mi)	1.0457
LOGVOL	Logarithm of the total volume of through traffic during the observation period	1.0358
URBAN	Fraction of the work zone length in an urban area	0.8884
PARK	Fraction of the work zone length with a parking lane before the construction period	-2.5927
COLLECT	Fraction of the work zone length on a collector road	0.4154
LSW	Average width of the left shoulder (ft)	-0.05922
RWW	Average width of the right of way (ft)	-0.00382
SHIFT	Indicator for traffic lanes shift in the work zone	0.2674
HWINT	Indicator for if high average work intensity (construction cost > \$35,000/(day × mi))	0.8861
ENFORCE	Indicator variable for police enforcement observed by project engineer	-0.8134

lower than 1, which means that as the work zone gets longer and lasts for a longer time period, the expected crash rate should be lower. However, in this simplified model, these two coefficients are slightly greater than 1, which suggests that longer work zones and longer working periods will exhibit higher crash rates. However, in both models, the coefficients are very close to 1, so it could be concluded that no significant effects were observed for the exposure variables.

The variable "Observed Police Enforcement" had a greater coefficient in the simplified model compared to the monthly observation model for the following two reasons: 1) the correlations among the explanatory variables, some of which are not included in the simplified model and could cause the coefficients of the remaining variables to fluctuate; and 2) the change in the observation, the simplified model's observation is an entire work zone as opposed to the monthly observation of the other model.

With the simplified model, the predicted crash frequency could be calculated using the equation provided below:

$$freq = Leng^{\beta_1} * Vol^{\beta_2} * e(K + \beta_3 * Urban + \beta_4 * Park + \cdots + \beta_{10} * HWINT)$$

The frequency calculated by this equation is the number of crashes expected in this work zone, for the entire work zone duration, without police enforcement. The βs in this equation are the estimated parameters from the model, while the K in the equation is the estimated intercept, as shown in the model output. By inserting the value of each input variable and β, the crash frequency could be calculated.

Then, the crash frequency with the presence of police enforcement could be calculated with a modified equation:

$$freq = Leng^{\beta_1} * Vol^{\beta_2} * e(K + \beta_3 * Urban + \beta_4 * Access + \cdots + \beta_{10} * HWINT + \beta_{11} * Enforce)$$

As can be seen from the equation, the only difference is the addition of the Enforce variable. With the crash frequency calculated from these two equations, the safety benefit of a planned work zone could be evaluated both with and without the presence of police enforcement. At this stage, the effect of police enforcement on crash severity cannot be assessed yet, and the prioritization would be based on the crash frequency only.

3.2.4 Monthly Observation Prediction Model

The two previous models aim at fitting the best models based on historical data and on different levels of data aggregation. However, when used for predicting for future work zones, not all of the variables used in those models would be available. Thus, a prediction model was estimated, using only the known variables for future work zones.

The model is essentially the same as the monthly observation model. Thus, the theory and model specification are not repeated here. The variables deemed not available for prediction purposes are listed below:

- Pavement condition variables;
- Project engineer observed enforcement variable; and
- ISP enforcement activity variables.

The pavement condition is available from the IRI database, which is maintained by INDOT Program Development Division. These data are usually updated once every few years and is impossible to obtain for any future years. Thus, any pavement condition variables were excluded in the prediction model.

The project engineer observed enforcement variable was excluded for the same reason. Before the construction took place, there would be no known work zone and no observation of police enforcement so this variable could not be included in the prediction model.

The ISP enforcement activity variables are similar to the previous two, but they are even more complicated. INDOT is currently using a point-based method to evaluate and assign a score to each individual work zone. This score is the current criterion used for ISP enforcement programming. Though it would be available prior to the construction and could eventually be used for our modeling, this score is considered to be highly endogenous with the dependent variable in our model, as discussed in the historical model with monthly observations. Thus, the ISP enforcement activity variables were also excluded from the prediction model.

On the other hand, some new insight was gained from the field observations and the "Speed Model," which is included in the next chapter. The Purdue Research Team found that, in terms of speed, work zones could be categorized into six broad categories, with our field observation covering four of them. Thus, four indicator variables denoting these four work zone categories were tested in the model. The overall model fitting statistics are shown in Table 3.6.

With the difference of three degrees of freedom, the model with categorization was not significantly better than the one without. However, when looking at individual variables, there was a variable with a P value of 0.2916 in the model without categorization. Thus, if only statistically significant variables were included in the model, the one with categorization should outperform the one without. Another benefit of using the model with the work zone categorization was that such categorization was used in the later Speed Models, and consistency among different components of this entire study was favored. The outcome of the model with categorization is shown in Table 3.7.

Comparing this model to the original historical work zone crash model with monthly observations, not only the pavement condition variable and observed enforcement variables were excluded but the indicator variables for full access control and for a collector road as

TABLE 3.6
Comparison of Goodness-of-Fit Statistics

Model with Categorization	
-2 Res Log Pseudo-Likelihood	1523.47
Generalized Chi-Square	535.45
Generalized Chi-Square/DF	1.01
Model without Categorization	
-2 Res Log Pseudo-Likelihood	1527.42
Generalized Chi-Square	542.17
Generalized Chi-Square/DF	1.02

well, due to low t-statistics. This was expected since the full access control and collector road basically represent the functional class of the road, while the added categorizations are doing basically the same thing. However, with the added work zone categorization variables, the new model performed even better than the previous historical model (which was estimated before the Speed Model and the categorization and which the Purdue Research Team believes could be improved with the categorization) and with one less degree of freedom.

Also, most of the variables had very similar estimates as in the original historical model, which adds to the confidence of this model. The interpretation therefore is not repeated as the effects are similar.

To further verify the goodness-of-fit of this model, the predicted crash frequency was plotted against the observed crash frequency in the work zones. While the monthly observations have 547 data points, which is cluttered and shows a lot of random fluctuation, when aggregated into the work zone level, the 70 pairs of data points exhibited excellent fit, as shown by Figure 3.2 and Figure 3.3.

While one could argue that, when modeling for disaggregated data and then presenting the aggregated results, some errors are expected to be cancelled out and much better fitting would be expected. In this case, though, with approximately eight observations for each work zone, there were not a large number of observations for each work zone. Also, accurate prediction at the work zone level is important for enforcement programming.

Thus, this model was included for prediction in the final programming tool for work zone enforcement. The crash frequency, according to the monthly observation work zone crash prediction model, is shown in the equation below:

$$A = L^{0.8713} * (D * V)^{0.8324} * EXP[-4.5387 * Cat_1 - 5.1792 * Cat_2 - 5.5850 * Cat_3 - 5.2151 * Cat_4 + 1.4102 * U - 2.1989 * P - 0.0537 * LS - 0.0060 * RW + 0.1920 * SH + 0.2271 * SP + 0.1685 * NovDec + 0.1695 * MayJunJul + 0.6655 * LO + 0.7038 * HI]$$

where:

A = expected number of accidents during the construction period,

L = work segment length (mi),

D = number of days,

V = average ADT during the construction period in 1000s veh/day,

Cat(1–4) = work zone categories, see Table 3.7 for definitions,

U = fraction of the work zone length in an urban area,

P = fraction of the work zone length with a parking lane before the construction period,

LS = average width of the left shoulder (ft),

RW = average width of the right of way (ft),

SH = 1 if traffic lanes shift in the work zone, = 0, otherwise,

SP = 1 if traffic lanes were split in the work zone, = 0, otherwise,

NovDec = monthly indicator for November and December, = 0, otherwise,

MayJunJul = monthly indicator for May, June and July, = 0, otherwise,

LO = 1 if the low work intensity (construction cost $<=$ \$10000/day/mi), =0 otherwise.

HI = 1 if the high work intensity (construction cost $>$ \$35,000/day/mi), =0 otherwise.

3.3 Summary

The first major component of this study, the work zone crash data analysis, was presented in this chapter; and there were several noteworthy achievements in this component.

First, a unique database was assembled by the Purdue Research Team. Since it is noticed that past studies basically all suffered from data availability issues, the Purdue Research Team carried out an INDOT project engineer survey and collected detailed work zone cross-sections and traffic management information for a substantial number of work zones (72 completed, with 70 having complete information), which is the most comprehensive in the literature (to the best of the authors' knowledge) in terms of the balance in detail and representativeness.

Second, several models were estimated to promote understanding of work zone crashes and to predict future work zone crashes. The monthly observation model was carefully specified using random effect to account for unobserved shared correlation, and variables regarding road characteristics, work zone features, monthly variations, and most importantly, police enforcement were included. There was no study found in the existing literature which featured a reasonable number of work zones that included such a level of detailed information. The work zone level observation model was less comprehensive, but it provided the possibility for low effort implementation. The prediction model was estimated at a much later stage compared to the monthly observation model. Even though the predicting model excluded the variables that

TABLE 3.7
Fixed Effect Parameter Estimates and Marginal Effects (with Categorization)

Variable	Variable Description	Estimate	t Value	Effect
WZ_Cat1	Intercept for Multilane freeway work zone sections without system interchange	-4.539	-7.10	N/A
WZ_Cat2	Intercept for Multilane freeway work zone sections with system interchange	-5.179	-8.16	N/A
WZ_Cat3	Intercept for Non-freeway work zone sections	-5.585	-12.63	N/A
WZ_Cat4	Intercept for Single-lane freeway work zone sections without system interchange	-5.215	-9.16	N/A
LOGLEN	Logarithm of the work segment length (mi)	0.871	8.31	N/A
LOGVOL	Logarithm of the total volume (in thousands) of through traffic during the observation period	0.832	12.51	N/A
URBAN[a]	Fraction of the work zone length in an urban area	1.410	4.03	4.097
PARK[a]	Fraction of the work zone length with a parking lane prior to the construction period	-2.199	-1.80	0.111
LSW[b]	Average width of the left shoulder (ft) prior to the construction period	-0.054	-1.66	0.948
RWW[b]	Average width of the right of way (ft) prior to the construction period	-0.006	-3.44	0.994
SHIFT	Indicator variable for existence of lane shift during the construction phase	0.192	1.74	1.212
SPLIT	Indicator variable for existence of lane split during the construction phase	0.227	1.38	1.255
NOVDEC	Indicator variable if the observation period is in November or December	0.169	1.97	1.184
MAYJUL	Indicator variable if the observation period is in May, June or July	0.170	2.57	1.185
LWINT	Indicator variable for low work intensity (construction cost $<$ \$10,000/(day $\times$ mi))	0.666	2.58	1.945
HWINT	Indicator variable for high work intensity (construction cost $>$ \$35,000/(day $\times$ mi))	0.704	1.93	2.021

[a]Fraction—the effect is per unit change (here per 1); thus the actual effect is smaller than the marginal effect.
[b]Continuous variables—the effect is per 1 unit change (foot); thus the actual effect is typically much higher than the marginal effect suggests.

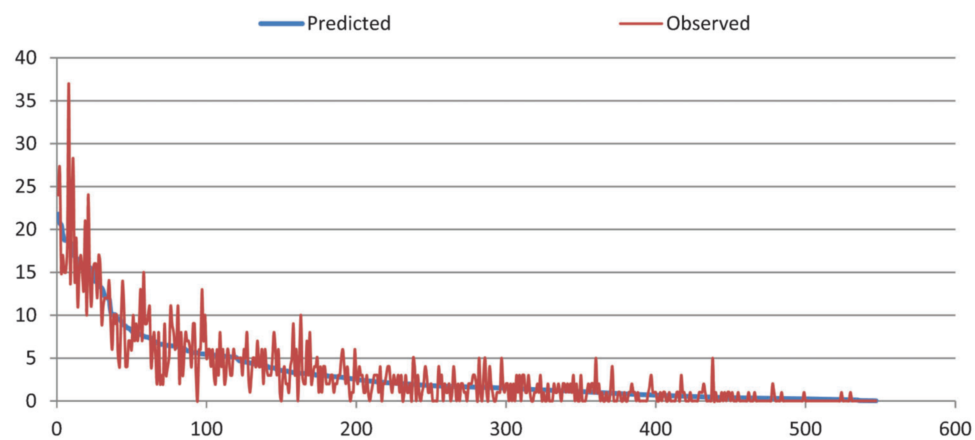

Figure 3.2 Predicted vs. observed crash frequency (monthly observations).

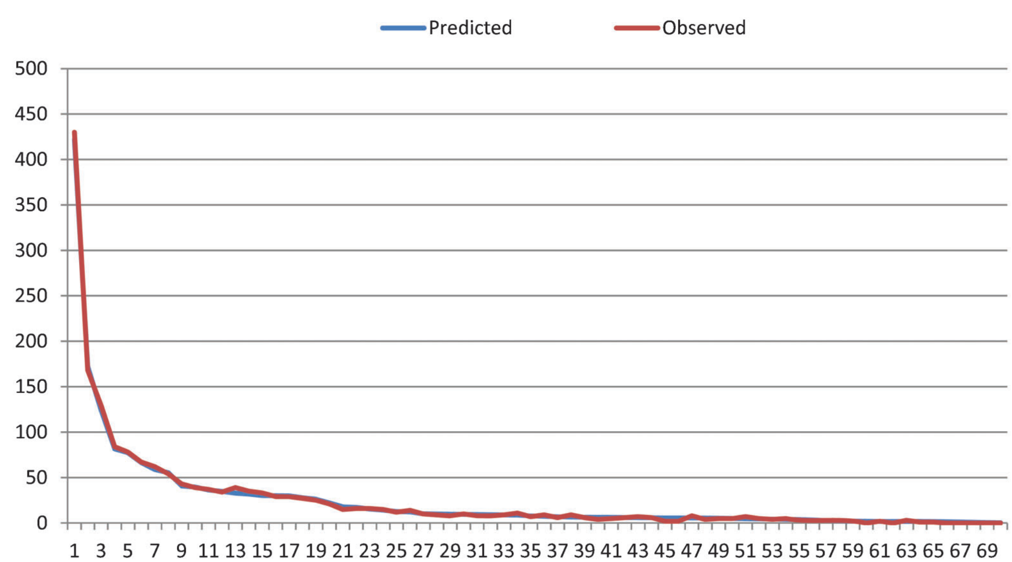

Figure 3.3 Predicted vs. observed crash frequency (work zone level observations).

would not be available for prediction purposes, it performs even better than the original model with new knowledge from other parts of this study.

Last but not least, the interim implementation plan of the Improved Prioritization Tool for the enforcement programming was designed, which incorporated the findings from the models into the current INDOT method. The interim Improved Prioritization Tool was sent to INDOT for the programming of the 2012 work zone enforcement, and its effectiveness can be evaluated. This interim tool will not be used in the future given that the final programming tool has been developed and is included in Appendix 2 only.

4. EVALUATION OF POLICE ENFORCEMENT STRATEGIES

The second major component of this study is to investigate the effectiveness of various police enforcement strategies through field evaluation. In Chapter 2, the current body of literature on police enforcement, especially in highway work zones, was reviewed and summarized. One striking issue identified was that even though a lot of studies evaluated the effectiveness of one or several police enforcement strategies, with some also covering different road classifications, there were very few comparison studies that were carried out in a systematic way. These studies were discussed in detail in Chapter 2.

Thus, our objective for this part of the study to fill this gap in the literature is to evaluate the effectiveness of different police enforcement strategies, in work zones with different features, by carrying out a "controlled" experiment. However, to carry out a truly controlled experiment could be practically impossible for various reasons:

- The duties of police officers determined that they might not always be able to perform the tasks planned for them in the study.
- The features of a work zone are decided by the need of the construction project and finding the right work zone to provide the combination of features desired from the experiment's point of view can be difficult.
- Work zone activities sometimes conflict with police enforcement or data collection activities, which can compromise scheduling data collection and police enforcement activities.
- Work zone features can change during the enforcement period in some cases, which makes the experiment controlling more difficult.
- Finally, the traffic conditions in the work zone also play a big role in the effectiveness of police enforcement, and congestions, construction vehicles entering and exiting, and crashes and other unexpected events could cause oscillation to the traffic, interfere with the effectiveness. All of these variables are impossible to control.

The Purdue Research Team, along with INDOT and ISP, made every effort to establish seamless coordination to help overcome the difficulties of designing an experiment that was as controlled as possible. These steps were taken to tackle the aforementioned difficulties:

- The police officers were advised to carry out "police presence" as defined by *Safe and Effective Use of Law Enforcement Personnel in Work Zones* (*26*), with the emergency lights on and being as visible to traffic as possible, with the officers having full authority to carry out a pursuit if they considered it necessary. GPS tracking units were distributed to each participating ISP officers to track each officer's activities. Thus, the Purdue Research Team had full knowledge of the enforcement activities and was able to correctly process the data.
- A list of all available work zones was provided by INDOT, and a preliminary screening of work zones was carried out during a SAC meeting with both Purdue and INDOT personnel. A final selection of work zones was done by interviewing INDOT Project Engineers. The authors visited the Project Engineers of each work zone prior to any field activities, retrieving detailed work zone features and discussing details about the data collection/ police enforcement activities, to prevent any potential conflicts between the construction activities and the data collection and police enforcement. The construction scheduling and data collection and enforcement scheduling was also coordinated at this phase.
- For some types of constructions (e.g., pavement rehabilitation), the construction process was fast-paced and the work zone progressed rapidly. As planned, the data collection was carried out for two full days within a week for each work zone, while such work zones could have progressed from one day to another, thus the same location could have different features for the two days of data collection. One such case was encountered out of the six selected work zones; and even though great effort was made, there are still issues involved with that work zone.
- Even though the capacity issue is a research objective of this project, there were some undesirable factors that caused congestion and traffic oscillation in work zones. Construction vehicle entering and exiting, lane changing maneuvers by drivers due to the "move-over law," and crashes that happened within the work zone all caused some unexpected and undesirable oscillation and interruption to the traffic flow. There are no effective ways to control such oscillation and interruption, thus the data was reduced accordingly.

The remainder of this chapter is organized as follows:

1. The field data collection activities are presented. All of the technical details including what was measured, how and where we measured them, and most importantly, the "Police Enforcement Experiment," are introduced in this chapter. All of the data collection details can be found either in this chapter or in a corresponding appendix.
2. The procedure for the data process is introduced in detail. The sample size requirement, the sampling technique, and the data extraction details are presented in this chapter. All of the raw data can be found in Appendix 3; all of the processed data can be found in Appendix 4.
3. The second main analysis component, the Speed Model, is presented. The theory of Multi-Level Modeling, the model specifications, and a detailed interpretation of the model can be found in this chapter.

4. A Speed Rebound Model is estimated in an effort to estimate the effective distance for police enforcement.
5. The findings and conclusions regarding police enforcement strategies are summarized.

4.1 Field Data Collection

4.1.1 Introduction

In the second stage of this project, the main research effort was to conduct a factorial experiment studying the effects of different police enforcement strategies in work zones with various features. The following sections discuss the selection of the performance measure, the data collection technique, the police enforcement strategy, the experiment design, the work zone selection, and an illustration of the field activities will be included. The detailed activities in all six work zones then are presented at the end of this chapter.

4.1.2 Performance Measure

Many studies have investigated the effectiveness of police enforcement in highway work zones. Most of these studies have measured point speed at or immediately downstream of the police enforcement (*21,37,38*), while some also measured the speed further downstream of the enforcement (*20,23*). The advantage of measuring the point speed is that it provides a very clear idea of the immediate effect of police enforcement, but there are disadvantages:

- Such a measurement technique is good for measuring the effectiveness of one single enforcement unit, but when multiple enforcement units are present, the selection of the measurement location will be less straightforward.
- As most past studies showed that effectiveness of police enforcement deteriorates quickly, the overall effectiveness over the entire work zone therefore cannot be obtained by point speed measurement, even with the addition of a downstream station.

Average speed was also used as a performance measure. With 13 Bluetooth speed measurement stations, Wasson et al. (*34*) measured average travel speed for 12 sections over a 12-mile long work zone. The space mean speed was calculated for both the beginning of the work zone and the entire work zone, but a speed profile was not provided.

Considering the disadvantages of measuring point speed, along with the objective and scope of this current study, the Purdue Research Team chose to use average speed as the performance measure to evaluate the effectiveness of police enforcement strategies.

4.1.3 Data Collection Technique

Traditionally, the technique most widely used for measuring average speed is to use pairs of video cameras. With the advance of technology, some new techniques are emerging. Bluetooth and GPS-based probe are among the most promising ones.

For the traditional video-based techniques, a pair of video camera is placed at both ends of the desired speed measuring segment. With synchronized clock on both cameras, the time taken for each vehicle to pass the segment can be easily calculated. The key in the video-based technique is to match the vehicles. License plate recognition techniques have seen wide implementation in toll collection, law enforcement, and other applications, which could also be used in this application. The downside is that commercial license plate recognition software is very expensive and it is thus clearly outside the scope of this study, while manual vehicle recognition will be time consuming.

The Bluetooth-based technique captures the Bluetooth signals from cell phones or other electronic devices in the vehicles and assigns a unique ID to each Bluetooth device. As the Bluetooth devices in vehicles pass each Bluetooth station along the roadway, each unique ID registers at the stations and eventually enables the calculation of the average travel speed. The downside of this technique is that it captures Bluetooth devices other than vehicles so the sample captured could be too small, could be a self-selected population (say, young people or business people), and could be repeated (two Blue tooth devices in one vehicle). Also, there is simply no way to capture the vehicle classification.

GPS-based techniques provide a variety of useful information about the probe vehicle. In this study, several GPS tracking units were purchased to track police vehicle activities, which provided us their location and point speed with time stamps, thereby enabling the calculation of all types of other variables for the police vehicles. The downside of this technique is obvious in that the GPS unit needs to be attached to the vehicles to capture such information. One study carried out in Spain (*45*) implemented this technique by stopping the vehicles and distributing GPS trackers. Two major issues prevent its implementation. First, such an intrusive method will be impossible to implement in the U.S. and also impossible on the freeways. Second, even if it were to be implemented, the intrusive nature of such a method would very likely change the behavior of the driver, as they would be aware of the device and that their speed was being monitored. Thus, this technique was not considered for this study.

Between the video-based technique and the Bluetooth technique, due to the sample selection issues associated with the latter, the Purdue Research Team decided to use the video-based technique. Vehicle recognition and matching was done manually by undergraduate research assistants. With a relatively small-scale data collection activity, plus a proper sampling technique, the amount of data processed could be managed to a reasonable level.

4.1.4 Enforcement Strategies

The objective for this part of the study is to identify the most cost-effective enforcement strategies for different work zones. The knowledge gained about police enforcement from the literature helped guide the design of the current study. Following is a quick review of the effectiveness and issues identified by other researchers:

- **Police Traffic Controller.** This strategy was found to be the most effective strategy in the comparison study by Richards et al. (*37*). The issues associated with this strategy were police officers being very reluctant to carry out such duties in the freeway environment, worrying about their own safety, and the lack of effectiveness if officers are away from their vehicles
- **Stationary Police Patrol.** This strategy was found to be only slightly less effective than police traffic controller in Richards et al. (*37*) and also was found to result in acceptable effectiveness in several other studies (*21,23, 34,38,46*). There are variants of this strategy, with the emergency light and radar on or off, but not enough evidence could be found to prove that one variant worked better than others.
- **Circulating Patrol.** This strategy was identified as the least effective in a comparison study by Richards et al. (*37*). It was shown to be effective in several other studies (*18,20*), but the effectiveness was generally not as good as the previous two strategies.
- **Camouflaged Enforcement.** This strategy is widely implemented in the State of Florida (*27*). However, strategies like this are more focused on the long-term effect, changing the culture of driving for the entire state, which is out of the scope of this study.
- **Automatic/Alternative Strategies (without police).** Several studies have used automatic or alternative enforcement techniques instead of police enforcement (*22,30–31,33*). While several techniques show significant effectiveness, a lot of them cannot be used in this study. Speed Photo Enforcement, for example, is not allowed by the Indiana legislature (*28*). Narrowing lane width, on the other hand, is out of the scope of this project. However, some of the alternative strategies could be considered in conjunction with police enforcement, such as CMS.
- **Multiple Enforcement.** Police enforcement using multiple units has not seen wide implementation in the literature, other than the Wasson et al. (*34*) study. Due to the lack of a comparison study, it is unknown whether more enforcement units will bring additional speed reduction. Based on the results from Wasson et al., however, too large a number of enforcement units in one work zone do not seem to be cost-effective.

With the effectiveness and potential issues of the popular enforcement strategies identified, the Purdue Research Team established the general rules for police enforcement in this study:

- Police Presence will be used for all the work zones. As defined in *Safe and Effective Use of Law Enforcement Personnel in Work Zones* (*26*), police presence consists of having police officers and vehicles present in work zones to be "a deterrent to speeding and aggressive driving" and to "gain the attention of drivers" but "not for enforcement," which is the most common practice for police officers in the work zones. Thus, in this study, the participating police officers stationed their vehicles at a pre-selected location, with their emergency lights on, and did not carry out pursuit unless necessary.
- Two different intensity levels of enforcement were planned for each work zone. For shorter work zones, there was one participating police office for the low intensity enforcement and two for the high intensity enforcement zones; and for longer work zones or those with on-ramps, there were two or four enforcement units for the low and high intensity enforcement, respectively.
- A Variable Message Sign (VMS) was used to display enforcement information to augment the effectiveness of police presence. To preserve the integrity of the message, the VMS was used only when enforcement was present in the work zone.

Initially, for better experimental design, and ultimately better analysis of the effectiveness of police enforcement, it was planned that police officers remain stationary without carrying out pursuit. During a meeting with ISP commanders and INDOT prior to the field activities, these enforcement strategies were approved by ISP commanders. However, during the enforcement activity in the Tippecanoe work zone (the first one), the police officers were pursuing speeding motorists quite actively. A conversation with the participating officer revealed their concerns, as quoted:

> "If we are present in a freeway work zone and do not pursue a vehicle which seriously violates the speed limit, we lose authority and will encourage the speeding behaviors."

This opinion expressed by the ISP officer is consistent with the observation made in (*17*) and (*18*) that the enforcement strategies may lose their effectiveness if there is no drivers' penalization. With respect to the state law and police officers and to preserve the authority, the general rules was altered as to "not carry out pursuit unless necessary." However, in the other work zones, the speeding problem was less serious and very little pursuit was apparent from the GPS trackers.

Also, the Purdue Research Team was interested in the effectiveness of VMS paired with enforcement. The VMS was planned for all of the work zones, but was not available for one work zone. The combinations of the strategies will be described in detail in the experiment design section.

4.1.5 Experimental Design

In observational studies, it is usually very hard to separate the effects of some highly correlated variables. However, in experimental studies, since researchers usually have control over the input conditions, such correlations do not usually exist. The idea of "factorial design" then is the central idea in the techniques of Design of Experiments (*46*). Factorial design means that, for all the factors that the researchers are interested in, their effects should not be compounded with others, which enables the identification of the effectiveness of these factors of interest. For other factors which could have an effect but are not of interest, they should be used as "block variables."

In this police enforcement experiment, many factors were believed to affect a driver's choice of speed, as grouped into the following categories:

- Work zone features
- Police enforcement strategies
- Traffic conditions
- Temporal effects
- Vehicle classification
- Driver behavior

Initially, the Purdue Research Team was interested in using both the police enforcement strategies and the work zone features as treatment variables. However, it was impractical to include work zone features as a treatment variable for several reasons. First, there were simply too many work zone feature variables, and including them all in a full factorial design would have required hundreds of work zones; second, since work zone features are not exactly controllable factors (we could only select from available work zones), a full factorial design including all of the work zone features was practically impossible. Thus, in the final design, the work zone features were used as block variables, with the same police enforcement strategies repeated for each work zone.

Police enforcement was the focus of this study, thus all of the police enforcement variables were used as treatment variables. For this factorial design, there were two enforcement variables: enforcement intensity and VMS; but for more detailed analysis, the relative location of enforcement with respect to the work zone (and also the data collection segment), the activity of the enforcement officer (patrolling and pursuit in some cases) were recorded by the GPS tracker. Two days of enforcement were planned for each work zone, which was a compromise between the sample size and the limited budget.

Traffic condition also affects speed, which includes traffic flow rate and truck percentage, and was clearly out of the control of the Purdue Research Team. Even though a clear picture about traffic conditions was not available before the field activities, it was very reasonable to assume it was highly correlated with the time of day and day of week. Thus, in this study, for most work zones (when there were no scheduling issues with ISP and INDOT project engineers), the two days of data collection were carried out on Tuesdays and Thursdays, during the same time period, which started about 10:00 am and ended about 5:00 pm. Enforcement strategies varied over a day and were flipped on the two days of data collection in order not to compound with the time of day effect. The design matrix is shown in Table 4.1.

From Table 4.1 one can see that the high and low intensity enforcement scenarios were flipped for the two days, and those effects were separated from the time of day and traffic condition effects. The VMS scheduling also was flipped to avoid confounding for each three-hour enforcement period. The VMS operated for one and half hours and off for the remainder of the three-hour period. VMS were not used when no enforcement was present.

A special note on the no-enforcement scenario: From the table, it would seem that no enforcement was used only during the noon period, which would be compounded with the time of day effect. The actual situation in the field was that the Purdue Research Team usually arrived at the scene and had the cameras set up earlier than 10:00 am; and in some cases, the camera continue to run after the police officer left the scene, thus there was a brief period of no enforcement both in the morning and the afternoon. But due to the uncertainty of the availability of these periods, it was not included in the design table.

The above schedule was the planned schedule. The actual scheduling varied somewhat by actual arrival/departure time and site specific conditions (e.g., officers left their locations to respond to crash). The actual schedule was documented daily for each work zone.

In terms of vehicle classification, it was suspected that different types of vehicles would have both different initial speeds and different reactions to the presence of police enforcement Benekohal (*20*). Although an uncontrollable factor, the classification was recorded during the data extraction process and was also considered a block variable. Finally, the driver behavior was considered to be random and was captured by the error term in the analysis.

With this design, all of the enforcement strategies, including the VMS, became factorial variables; and all potential compounding was eliminated or at least minimized by this design. The work zone features and vehicle classification were used as block variables, the effects of which were separated from the enforcement strategies.

TABLE 4.1
Experimental Design Matrix for Work Zone Enforcement

Day One	10:00 am–11:30 am	High intensity enforcement	VMS ON
Day One	11:30 am–1:00 pm	High intensity enforcement	VMS OFF
Day One	1:00 pm–2:00 pm	No enforcement	VMS OFF
Day One	2:00 pm–3:30 pm	Low intensity enforcement	VMS OFF
Day One	3:30 pm–5:00 pm	Low intensity enforcement	VMS ON
Day Two	10:00 am–11:30 am	Low intensity enforcement	VMS OFF
Day Two	11:30 am–1:00 pm	Low intensity enforcement	VMS ON
Day Two	1:00 pm–2:00 pm	No enforcement	VMS OFF
Day Two	2:00 pm–3:30 pm	High intensity enforcement	VMS ON
Day Two	3:30 pm–5:00 pm	High intensity enforcement	VMS OFF

4.1.6 Work Zone Selection

As previously mentioned, there were many candidate work zone features we wished to include in the factorial experiment design, but the budget, resources, and appropriate work zones for data collection were limited, which made it difficult to find work zones with the desirable combinations of features. Therefore, the Purdue Research Team decided not to use the work zone features as a treatment variable but to alternatively treat them as block variables.

INDOT has provided a list of appropriate work zones for the Purdue Research Team to consider for field activity. Based on the research need, the Purdue Research Team first selected a subset of work zones with the desired features. Based on the objectives in this study, the work zone selection criteria were:

- Freeway or arterial work zones, with mainly uninterrupted traffic flow
- High speed roadways, with the original speed limit at least 45 mph
- VMS boards available from the corresponding INDOT sub-districts
- Relatively long segments suitable for measuring speed
- The schedule of the construction with which the Purdue Research Team, and ISP must comply
- Project originally planned for enforcement to ensure no enforcement dollars were wasted
- INDOT project engineer's permission was obtained for liability issues

For the subset of the work zones that met the criteria, the Purdue Research Team conducted a site visit to in order to prepare a preliminary data collection plan, and then met with INDOT project engineers to discuss the study's detailed activities and to gain their permission to proceed. The site visit further eliminated some potential work zones due to following discussed considerations:

- For a non-freeway work zone, it could be too close to traffic signals, or there could be other interferences with the traffic flow that could interrupt the traffic flow and render the measurement of speed pointless.
- Only one work zone would be included for multiple work zones located close together. This was the case for I-465 W, where multiple construction projects were occurring at the same time. The consideration for this decision was that limited knowledge would be gained with the addition of a nearby work zone.
- There are areas where there are no safe locations to install the cameras or to park police vehicles due to the construction activities. Some efforts were made to accommodate these areas while in some cases the work zones were abandoned for the study.

In the end, six work zones were designated for the data collection. A summary of these work zones is provided in Table 4.2.

As can be seen from Table 4.2, the work zones selected for data collection have various features. Also, due to the construction activities, not all of the work zones were designed the same, which further complicated the issue. A unified approach for the camcorder installation and police vehicles enforcement strategies was planned to make sure these activities were as consistent as possible and the data collected as useful as

TABLE 4.2
Summary of Work Zone Features

Work Zone	Project Type	Length	Lanes Open (One Direction)	Location	Road Classification	Speed Limit (Original/ Reduced)	Special Features
Tippecanoe Work Zone	Pavement rehabilitation	1.1	2	Rural	Freeway	65/45	Barrier (left), lane shift
Greenfield Work Zone	Adding travel lane	7.74	2	Rural	Freeway	70/45	Barrier (both)
Airport Work Zone	Bridge replacement & adding travel lane	2.22	3	Urban	Freeway	55/45	Barrier (both), lane shift, lane closure, system interchange
South Bend Work Zone	New road construction (overhead bridge)	0.63	1	Rural	Arterial	45/35	Lane closure, alleys
Fishers Work Zone	Bridge reconstruction (overhead)	0.62	2	Rural	Freeway	70/45	None
Terre Haute Work Zone*	Pavement rehabilitation	5.83	1	Rural	Freeway	70/45	Barrier, lane closure, on/off ramps
Terre Haute Work Zone*	Pavement rehabilitation	5.22	1	Rural	Freeway	70/45	Barrier, lane closure, on/off ramps

*The Terre Haute work zone is a very long (50 $\pm$ miles) work zone, with several five-mile construction segments. The two days of data collection were conducted at different segments due to interference with construction activities.

possible for analysis. The general equipment placement and police enforcement locations are discussed first below, and then the six work zones are introduced in the order of the dates when the data collection was conducted.

4.1.7 Camcorder Placement

Up to four digital camcorders were placed alongside the work zone and its approaches: one at the beginning, one in the middle, one at the end, and one upstream of the work zone, usually at the beginning of the advance warning area. The JTRP Mobile Traffic Lab (labeled "Purdue Van" in the illustration) was used at the upstream location. Not all work zones used all four camcorders. For instance, some short work zones had no camcorder in the middle of the work zone while non-freeway work zones did not have a camcorder in the advance warning area. Also, the location of the camcorders sometimes was pushed further upstream or downstream due to the lack of a proper location in the work zone.

The selection of the location for the camcorder inside the work zone was important since it defined the data collection segment. Thus, such locations were always chosen at some distinct feature (e.g., a ramp) or the beginning of the actual construction area, etc.

The general placement of camcorders is illustrated in Figure 4.1.

The camcorders were mounted on tripods at locations close to the traffic but far enough as not to cause any visual distraction to the drivers. Rain covers were used for each camera, which not only protected the cameras from precipitation but also provided some concealment. The Purdue Research Team field crew tried to mount the camcorders behind concrete barriers, bridge piers, or other objects where possible, to make them as inconspicuous as possible.

4.1.8 Police Vehicle Locations

For enforcement vehicles, even though the final locations were decided upon due to site-specific conditions and also the number of available police officers, a generalized plan was also prepared beforehand. First, the work zones were categorized into "large" and "small" groups. Large work zones were those either long in length, which provided a chance to see the effective distance of the police enforcement, or there were ramps inside the work zone, which required additional police vehicles to be present to the on-ramp traffic. Small work zones were those both short in length and not having ramps inside, and small work zones did not require a large number of police vehicles.

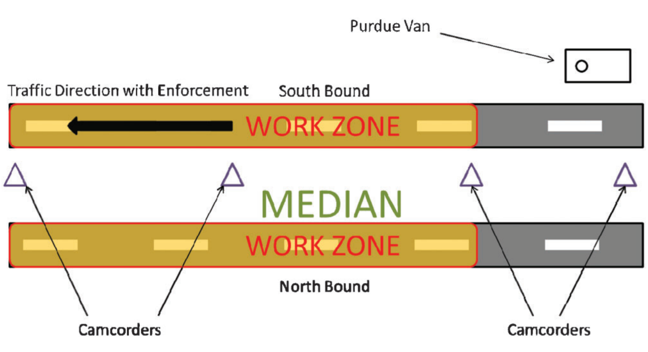

Figure 4.1 Camcorders placement in work zones.

The positioning of police vehicles in a large work zone is illustrated in Figure 4.2. As can be seen, one of the police vehicles was placed in the advance warning area, one at the beginning of the work zone, one inside the work zone, and one at the end of the work zone. An effort was made to place the police vehicles and camcorders at the same spot where possible. Also, in the original planning stage, the police vehicle in the end of the work zone was used for pursuit; but based on the activities we retrieved from the GPS tracker, most of the time these police vehicles remained stationary and performed police presence only.

During the low intensity enforcement of the large work zones, the placement of the two police vehicles was not fixed. Other than the end of the work zone, the police vehicles could have been stationed at any of the other three locations to test the effectiveness of different combination; but there was always one police vehicle at the beginning.

For the smaller work zones, there was always a police vehicle at the beginning of the work zone. As for the high intensity enforcement, the second police vehicle was placed inside the work zone or upstream of the work zone, in order to test the effectiveness of different combinations.

Finally, the enforcement locations depended on the site conditions. The police officer needed to be stationed at a safe and non-intrusive location (if they were too close to the travelled lane, drivers could feel obligated to comply with the "move over" law). Thus, the actual locations were somewhat different from the planned strategies. Detailed information is provided for each work zone in the next section.

4.1.9 Detailed Data Collection Activities

In this section, detailed information about the activities in all six work zones is provided. The location, construction activities, work zone characteristics, data collection activities, and police enforcement activities are provided.

IR-33296 "Tippecanoe Work Zone." This work zone was a pavement patch and rehabilitation project, located on I-65, between milepost 167.1 to 168.24, south of SR-38, outside Lafayette. The Purdue Research Team collected traffic data on the northbound direction of this work zone on May16 and May18, 2011. During the time of data collection, the traffic was managed with a temporary lane (on the right shoulder); thus, there were two lanes open to traffic, there was a lane shift to the right, and there was

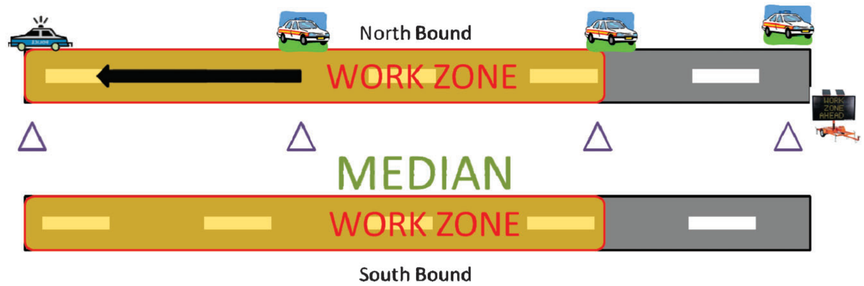

Figure 4.2 Typical police vehicle placement in work zones (high intensity).

a concrete barrier immediately adjacent to the travelled lanes on the left side. The speed limit of this work zone was 45 mph compared to the 65 mph speed limit before the construction. The work zone was 1.098 miles in length; and due to the site conditions, the distance between our pair of camcorders was 2.458 miles, at 1.36 miles before the work zone and the entire length of the work zone.

The police enforcement schedule was planned according to the general strategies, but the final strategy in this work zone was quite different from the planned scenarios due to two facts:

1. Some officers refused to turn the emergency lights on while performing stationary enforcement in the work zone, stating that the lights should not be turned on unless there is an emergency.
2. There were cases of speeding in this work zone while police officers were present in this work zone, and multiple pursuits were carried out by the officers. As for our request of staying stationary as much as possible, one officer stated: "If we are present in a freeway work zone and do not pursue a vehicle which seriously violates the speed limit, we lose authority and will encourage the speeding behaviors."

Due to these two facts, the enforcement strategies were quite different in this work zone compared to all of the other work zones; but the stationary locations for the police vehicles are still according to the plan, which is shown in Figure 4.3.

The final enforcement schedule (along with the VMS information) is presented in Appendix 3 due to its large size.

Due to miscommunications, the VMS planned for this work zone was placed at the wrong direction of the freeway. With the help of the INDOT project engineer and the contractor, the Purdue Research Team managed to use one of the contractor's VMS boards to display our enforcement message. Therefore, the final schedule of the VMS was different from a typical planned schedule, with the sign being off for the first day of data collection and on for the second day.

IR-31104 "Greenfield Work Zone." The project at this work zone was to add a travel lane to the I-70 freeway. The project was on I-70, between Post Road and past Mount Comfort Road to the east of Indianapolis. The Purdue Research Team collected traffic data on the westbound direction of this work zone on June 7, June 9, and July 14, 2011. During the time of data collection, the construction activities were mainly in the median, with both existing lanes open to traffic, and there was a concrete barrier immediately adjacent to the travelled lanes on both sides. The speed limit of this work zone was 45 mph compared to the 70 mph speed limit before the construction. The work zone was 7.7388 miles in length, and the ramps for Mount Comfort Road were inside the work zone. To avoid the ramps, both data collection sections were selected to be farther downstream inside the work zone. The first section was located 3.01 miles from the start of the work zone and was 1.39 mile in length; and the second section was located 4.4 miles from the start of the work zone and was 1.75 mile in length. The work zone layout, camcorder placement, and police enforcement locations are shown in Figure 4.4.

The enforcement strategies and the VMS schedule followed the general strategy in this work zone, with the exception that on July 14, 2011, only three police vehicles were available for the high intensity enforcement, with one officer not being able to participate. As previously mentioned, there were on/off ramps at

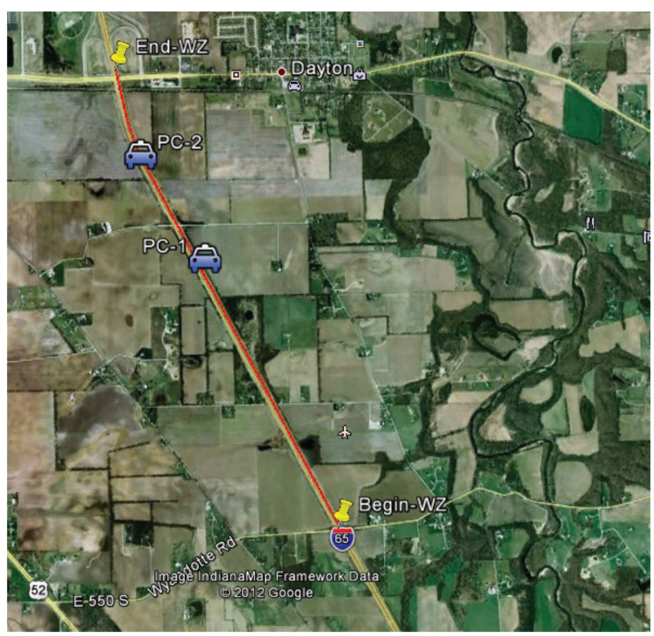

Figure 4.3 Layout of the Tippecanoe work zone. (Image from Google Earth.)

Figure 4.4 Layout of the Greenfield work zone. (Image from Google Earth.)

Mount Comfort Road; and we selected the downstream location for our video data collection. One police vehicle (in the middle of the work zone) was located right after the on ramp to cover the on ramp traffic, which was unable to see the upstream police vehicles. The final enforcement schedule is shown in Appendix 3.

IR-30020 "Airport Work Zone." The project at this work zone was to replace and add travel lanes on I-465 W, between SR-67 and US-40, near the Indianapolis airport. The Purdue Research Team collected traffic data on the northbound direction of this work zone on June 21 and June 23, 2011. During the time of data collection, there were construction activities both in the median and to the right side, with three lanes open to traffic and a concrete barrier immediately adjacent to the travelled lanes on the left side. There were multiple on/off ramps in this section, with all the ramps to the right side. The speed limit of this work zone was 45 mph compared to the 55 mph speed limit before the construction. The work zone was 1.96 miles in length, which covers the interchanges with I-70 and the Sam Jones Expressway, which makes avoiding the ramps impossible. Based on the site conditions, three camcorders were installed in this work zone. The first one was located at the start, the third one at the end, and the camcorder in the middle was located right after the on ramp from I-70. With this placement, there were a lot of missing vehicles between the first pair of camcorders, due to the large off ramp traffic volume at I-70. For the second pair, due to a small volume exiting at Sam Jones Expressway during our hours of data collection, the proportion of missing vehicles was much smaller compared to the first pair. The work zone layout, camcorder placement and police enforcement locations are shown in Figure 4.5.

The VMS schedule followed the general strategy in this work zone, while the enforcement strategy was different from the general ones. First of all, on both days, only three police vehicles were available for the high intensity enforcement, with one officer not being

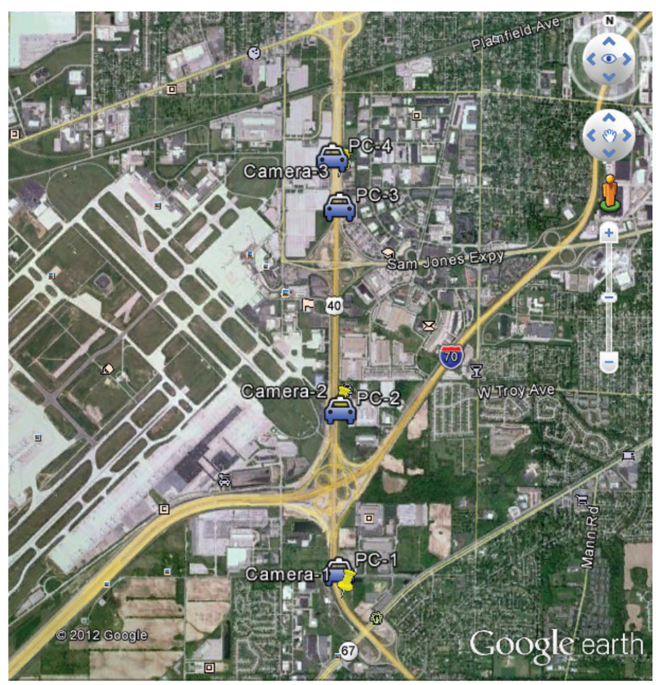

Figure 4.5 Layout of the airport work zone. (Image from Google Earth.)

able to participate. Secondly, as previously mentioned, there were two major interchanges within this work zone, thus two police vehicles were assigned to the on ramps (see Figure 4.5). Thus, the strategy for this work zone was one police vehicle for the start of the work zone and two police vehicles inside the work zone that were placed right after the on ramps. The final enforcement schedule is shown in Appendix 3.

IR-30127 "South Bend Work Zone." The project at this work zone was construction of a bridge over the existing US-31 highway. The bridge under construction is for the proposed US-31 while the work zone is on the existing US-31, between SR-4 and US-20, in south suburban South Bend. The Purdue Research Team collected traffic data on the northbound direction of this work zone on July 19 and July 20, 2011. During the time of data collection, there was temporary lane closure, with only one lane open to northbound traffic. There was heavy construction truck traffic entering and leaving the construction site through the data collection road section as well. There were multiple minor intersections in this section, but the turning traffic volume was expected to be low. The speed limit of this work zone is 35 mph compared to the 45 mph speed limit before the construction. The work zone was 0.63 miles in length, thus only two camcorders were installed one at the start and the other at the end of the work zone. With such placement, missing vehicles would be expected between the camcorder pair, but that volume was expected to be low. The work zone layout, camcorder placement, and police enforcement locations are shown in Figure 4.6.

This work zone was categorized as a small work zone, thus only up to two police vehicles were planned for the enforcement. Also, since this was a relatively low speed, non-freeway work zone, a VMS was not used. The strategy of the enforcement followed the general plan, with high intensity enforcement having two police vehicles, one vehicle at the start and the second vehicle at the lane closure. The final enforcement schedule is shown in Appendix 3.

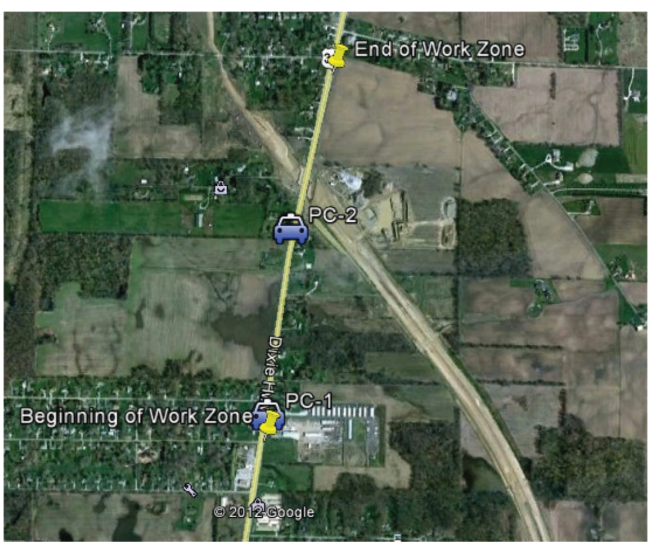

Figure 4.6 Layout of the South Bend work zone. (Image from Google Earth.)

IR-31669 "Fishers Work Zone." The project at this work zone was constructing a bridge over the existing I-69 freeway. The bridge under construction was located in the northeast suburban town of Fishers on 126th Road, but the construction affected I-69, which is near 126th Road. The Purdue Research Team collected traffic data on the southbound direction of this work zone on October 21 and October 25, 2011. During the time of data collection, there were not many special work zone features on I-69, with only a very short section of concrete barriers under the bridge and some shoulder work upstream of the bridge. There was neither lane closure nor ramps inside the work zone. The speed limit of this work zone was 45 mph compared to the 70 mph speed limit before the construction. The work zone itself was 0.62 miles in length, while the advance warning area was approximately one mile. Two pairs of camcorders were installed, one for the work zone and the other for the advance warning area. No missing vehicles were expected between the camcorder pairs. The work zone layout, camcorder placement, and police enforcement locations are shown in Figure 4.7.

Both the enforcement and the VMS schedule followed the general plan. One exception was that the VMS was withdrawn in error from the work zone on October 25 at around 2:00 pm by mistake, thus the VMS was not operating for the afternoon period of October 25. Since this was considered a small work zone and for the high intensity strategy, two police vehicles were stationed at the start of the work zone and the start of the advance area as compared to only one police vehicle at the start of a work zone scheduled for low intensity enforcement.

When the Purdue Research Team arrived at the scene on October 21, an unexpected issue was encountered. Before the scheduled enforcement time period was to begin, there was an ISP officer actively enforcing at this work zone. We learned from the officer that he was the regularly scheduled INDOT work zone patrol officer. Upon our request, this officer changed his strategy and was stationed at an upstream location of the northbound direction, which was assumed to have no effect on the southbound traffic inside our data collection sections.

The final enforcement schedule is shown in the Appendix 3.

IR-34111 "Terre Haute Work Zone." This work zone was for a pavement rehabilitation project on I-70, from SR-59 to Ameriplex Parkway near the Indianapolis International Airport. This was a very long work zone which measured 46 miles in length, with multiple construction sites inside. The construction activities require lane closure so the construction sites were

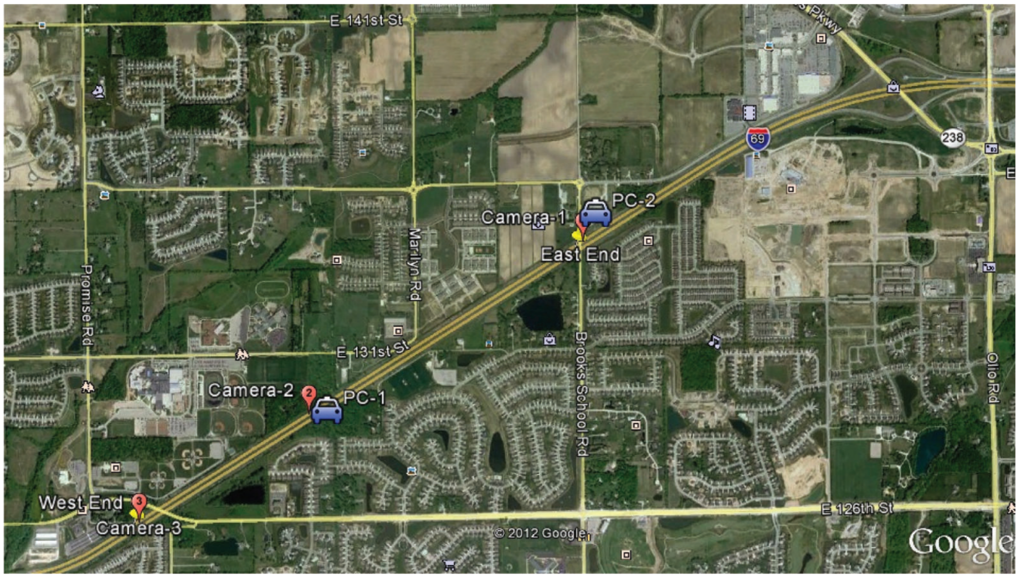

Figure 4.7 Layout of the Fishers work zone. (Image from Google Earth.)

limited to five miles in length in order to maintain a reasonable traffic flow. Also, the construction activities progressed rapidly inside the work zone so on the two days of data collection activity, the data collection sites were not at the same place due to the change in the construction site.

Due to the aforementioned conditions, the two days of data collection activities in this 46-mile-long work zone were carried out in different locations, with one day of collection for each. These two locations could be reasonably considered to be two individual work zones. For both work zones, The Purdue Research Team collected video data for the lane closure sections (with lane closure, the actual construction site was about five miles in length); for the advance warning area (with no lane closure and normal speed limit of 70 mph, but with warning signs indicating "45 mph ahead"); and for the second site downstream of the work zone (with normal two travel lanes and 70 mph speed limit, where we suspected serious speeding would take place).

No work zone features of any kind existed in the advance warning areas other than the warning signs, and there were no work zone features at all in the downstream section. Inside both construction sections, there were lane closures while parts of the sections were marked with plastic cones, and the parts with actual construction work occurring had concrete barriers immediately adjacent to the travelled lane. In both construction sections, there were on/off ramps. For the first section there were two pairs of ramps to/from state highways; and for the second section, the ramps were to/from a rural arterial. Thus, more missing vehicles would be expected for the first site. During the data collection periods (for both days), serious congestion was observed, and the Purdue Research Team had reasons to believe that this congestion was due to construction activities rather than purely heavy traffic or police enforcement activities.

The layouts of both sites are shown below in Figure 4.8 and Figure 4.9 along with the enforcement strategies.

In the first site, the police enforcement followed the general plan. Four police vehicles were scheduled for the high intensity enforcement, with one stationed near the start of the advance warning area, the second at the start of work zone, the third inside the work zone at the actual construction site, and the fourth at the end of the work zone. The VMS schedule also followed the general plan, but due to the progress of the work zone, the VMS was located 12.8 miles upstream of the start of the work zone, thus the effectiveness was in doubt.

In the second site, the police enforcement was the same as in the previous site. The only exception was that several rear-end crashes happened at about 3:30 pm, which required the police officers to respond to the crash scenes (near the end of the work zone), thus, the location changes. However, due to congestion issues, that part of the data was not used for our analysis so the change of locations for the police officers would not affect our analysis. The VMS schedule also followed the general plan. However, again, due to the progress of the work zone, the VMS was located 2.4 miles into the work zone (as shown in the figure) so once again, the effectiveness of VMS should be treated with caution.

The final detailed enforcement activity log is shown in Appendix 3.

4.2 Data Extraction and Process

With video data collected from the selected work zones, the next step was to utilize these traffic data to analyze how various factors affected drivers' speed choices in the work zones. To facilitate this analysis, traffic and other information needed to be extracted from the video and other raw data.

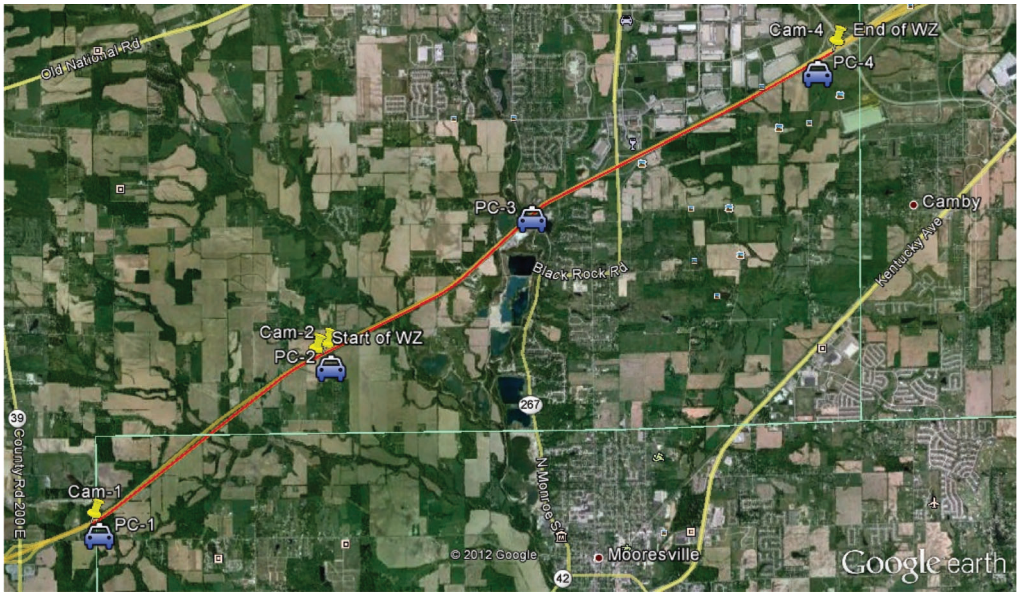

Figure 4.8 Layout of the first site of the Terre Haute work zone. (Image from Google Earth.)

There were three broad categories of data available from our documentation, video, and GPS tracking data.

1. Work zone features
2. Traffic characteristics
3. Police enforcement activities

Work zone features were the simplest to document as they came directly from the site conditions. However, the traffic characteristics and police enforcement activities required extraction. Before extracting the data, the Purdue Research Team listed the information that was desirable for our analysis and was available from the data we collected:

Traffic characteristics

- **Traffic Flow Rate.** Speed is known to be affected by traffic volume; thus, the real-time traffic flow rate would be an important contributing factor for the speed.
- **Percentage of trucks.** Tractor-trailer combinations and single unit trucks usually travel at lower speeds than passenger cars so the percentage of truck traffic would affect speed.
- **Time of Day.** It is commonly known that speed varies across a day so the time of day would affect speed.

Police enforcement activities

- **Number of Police Vehicles.** It is expected that a greater presence of police vehicles would produce a better speed reduction effect so the number of police vehicles would be expected to affect speed.
- **Enforcement Strategy.** The past literature indicates that the effectiveness of different enforcement strategies on speed reduction varies so the type of strategy utilized in the analysis would affect speed.
- **Location.** We know from the literature also that the effectiveness of police enforcement deteriorates rapidly spatially so the relative location of police enforcement and data collection sections will be used for analysis.
- **VMS.** The on/off condition and the location of the VMS from the data collection sections is also expected to have an effect.

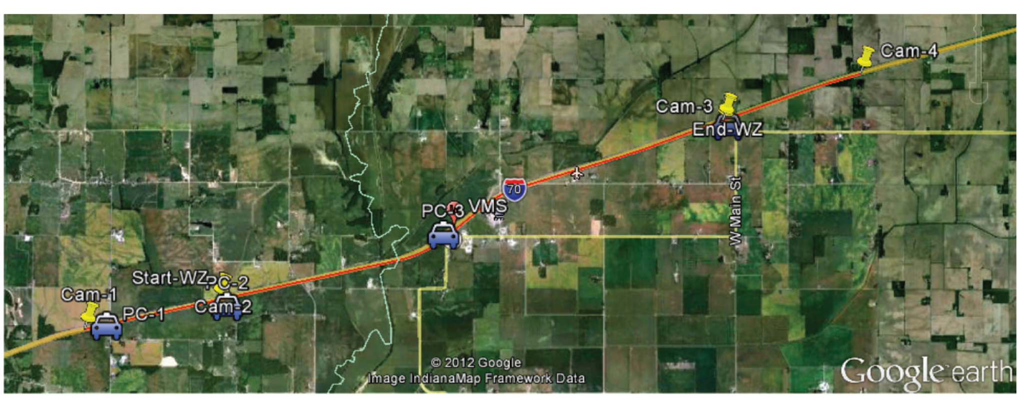

Figure 4.9 Layout of the second site of the Terre Haute work zone. (Image from Google Earth.)

All of the information listed above, along with speed, was available from either the video data or the GPS tracking data. The following section will discuss in detail how these data were extracted and processed.

4.2.1 Data Inventory

A total of 13 days of video data were collected from six work zones for a total of six to seven hours per camcorder (limited by the battery life and memory space). However, since the vehicles had to appear on pairs of camcorders in order to calculate their speed, the effective length of video for the entire work zone was the overlapping portions of the video files, which was slightly shorter, depending on how much time it took to install the camcorders. The total effective video length for each day is shown in Table 4.3.

One day of video data (June 7, 2011, at the "Greenfield" work zone) was accidentally lost due to human error, but the Purdue Research Team conducted another day of data collection in order to maintain the two days for each work zone convention.

Also, not all of the collected video data could be used. Since the purpose of our analysis was to study how the work zone features and enforcement strategies affected speed, we attempted to control for the traffic characteristics and some events happening within the work zone that could greatly affect the traffic flow (e.g., construction activities that affect the travelled lanes, crashes, oversized load fleets). Most of these events were documented, and the portions of video with documented abnormal events were not included in our analysis.

4.2.2 Data Extraction Methods

Basic procedure. Since automated license plate matching techniques were not available to the Purdue Research Team due the budget constraints of the project, two undergraduate research assistants were hired to process the video data.

For each work zone beginning with the most upstream camera, one undergraduate research assistant, starting from a pre-selected time (introduced later), controlled the video playback software and then paused the video when the target vehicle arrived at a pre-selected location (also introduced later). Both undergraduate research assistants then tried to identify this vehicle with as many features as possible while the second undergraduate research assistant recorded the time, the type of vehicle (passenger car, single unit truck, or truck-trailer), and other information to help match this vehicle in the other camcorders. Also, a unique ID was given to each vehicle. Then, the first undergraduate research assistant resumed the video and repeated the process for the next vehicle. They recorded as many vehicles in the first camcorder as they felt comfortable for matching in the later camcorders.

Then, they proceeded to the second camcorder, with the first undergraduate research assistant still operating the video playback software. They tried to identify all of the recorded vehicles in the second camcorder when there was no ramp or intersection in the work zone section. The most important part was to match the vehicles from those recorded in the first camcorder. Once a vehicle was confirmed for matching, its vehicle ID was recorded; and the time and order of their passing the second camcorder were recorded. For longer work zones, the order of vehicles sometimes changed and the time of arrival varied so the undergraduate research assistants were advised to check for an appropriate time period in order not to systematically miss the very fast or very slow vehicles. The above described process was repeated until all the vehicles were matched.

There were several reasons why vehicles were missing from the second camcorder (unable to be matched). The most obvious reason was due to the existence of ramps or intersections in the section. The second reason was that the vehicle was a construction vehicle or other official vehicle, which might have entered the construction area or turned around using the median opening. Another major reason for the inability to match was due to a vehicle being blocked by other larger vehicles. Since our camcorders all were installed in the median or roadside, vehicles in the far side lane could have been blocked by large vehicles, especially truck-trailers. For such situations, the undergraduate research assistants mark the vehicle as missing.

If there were more than two camcorders for the same work zone, the undergraduate research assistants repeated the process until the last camcorder was reviewed.

Sample selection. Due to the lack of automated technology for the data processing, it was too costly to process all the collected video data manually. Thus, only a sample was selected for processing.

TABLE 4.3
Available Video File Length

ID	Work Zone ID	Dates	Total Length of Available Video File
1	33296	05/16/2011	6:10:53
2	33296	05/18/2011	6:20:01
3	31104	06/07/2011	Lost*
4	31104	06/09/2011	12:55:20 (two segments)
5	30020	06/21/2011	12:44:42 (two segments)
6	30020	06/23/2011	13:27:28 (two segments)
7	31104	07/14/2011	12:14:28 (two segments)
8	30127	07/19/2011	6:26:10
9	30127	07/20/2011	6:26:59
10	31669	10/21/2011	12:45:34 (two segments)
11	31669	10/25/2011	12:00:00 (two segments)
12	34111	11/8/2011	7:46:20
13	34111	11/11/2011	12:53:00
	Total		**122:10:55**

*Lost due to human error when processing the data.

There are two widely used sampling techniques: systematic sampling and free-flow sampling. Benekohal et al. (*20*) defined and compared these two sampling techniques. The advantage of the free-flow sampling technique is that it better reflects the real desired speed of the drivers, free from the obstruction of other traffic, and the true effectiveness of police enforcement on those speeding drivers can be better captured as well. However, this technique best works with point speed measurement. In order to measure a vehicle's average speed in the work zone using the free-flow sampling technique, it is impossible to tell whether a vehicle is free flowing over the entire length of a work zone. On the other hand, the systematic technique samples vehicles in a systematic way, with all of the vehicles having an equal chance of being sampled. For the purpose of this study, since the objective is to maximize the benefits of the police enforcement dollars, the systematic sampling technique was preferred over free-flow sampling since it better reflects what is really happening in the work zone and what the effects would be. The effect of heavy traffic could be captured during the modeling process because the traffic volume was also measured.

Based on the data needs and the budget, the Purdue Research Team decided to sample 50 consecutive vehicles for each 30 minutes. For work zones with no ramps or intersections located inside, the objective was to sample 50 matched vehicles that could be positively identified in all camcorders; and for the work zones with ramps or intersections, 50 vehicles from the first camcorders were sampled regardless of the number of final matches.

The starting time of the sampling was carefully selected based on several factors: the start and end time of each camcorder, the time when the police enforcement strategy changed, and the time of documented abnormal traffic conditions. The Purdue Research Team chose the starting time to avoid all these time points and to give enough cushion around these events. In case some of these time points were hard to avoid, some individual periods were moved back or forward for ten minutes. It was felt this strategy would cause very little bias in terms of sampling but could significantly improve the quality of the sampled data.

Location selection. When the camcorders were installed in the field, the Purdue Research Team set the camcorders in such a way as to capture a relatively broad field of view for the following three reasons:

1. License plate matching was not used, rather vehicles were identified by features; thus, very high definition was not required.
2. The camcorders were mounted on only one side of the road, and vehicles sometimes could have been blocked by other vehicles. A broader field of view reduced the chance that a vehicle was blocked for the entire time while passing the camcorder.
3. Some roadside or pavement features helped the Purdue Research Team to pinpoint the location of the measurement and thereby more accurately measure the distance between camera pairs.

Therefore, to be consistent and accurate, for each camcorder, one specific location was chosen, and the undergraduate research assistants recorded the time when each vehicle arrived at that location. The general principles for selecting these locations included:

1. The locations were reasonably away from the edge of the field of view, thus making it easier for the undergraduate research assistants to react.
2. The locations were situated at or aligned with some recognizable features (e.g., bridges, recognizable roadside features like billboards, overhead signs, locations where the pavement type changed, the start/end of guardrails, and other features). These features were then used to mark the section length in Google™ Earth.
3. The locations were as close to the start/end of the work zone as possible.

All locations were selected by the Purdue Research Team and were marked in Google™ Earth. The undergraduate research assistants were instructed to use these locations before they processed the video data.

4.2.3 Extracted Elements

In addition to the speed of vehicles, other information was also extracted from the video. The Excel table the undergraduate research assistants used to record vehicle information contained the following variables:

- Vehicle type
- Vehicle description
- Time stamp when passing the camcorder
- Lane of traveling
- Vehicle ID (for each camera)
- Vehicle order (not for the first camera)

With the above listed information, some additional data were extracted through additional processing. All of the variables extracted from the video data are shown below, along with a description of the process:

- **Speed.** Speed was the most important information extracted from the video data. The distances between the camcorder pairs were measured from Google™ Earth and documented by the Purdue Research Team. The travel time for each vehicle to pass through this distance was the difference between the time stamps when a vehicle passed each camcorder. Then, the speed was calculated as the distance divided by the travel time.
- **Traffic Flow Rate.** Using the time stamp of each passing vehicle, the time taken for each vehicle to pass the camcorder location was calculated. Then, using the number of vehicles and time elapsed, the traffic flow rate was calculated for the time when the traffic data were extracted. Please note that the traffic information from the first camcorder was used to calculate the traffic flow rate. It could also be calculated for the other cameras; but due to matching issues, the traffic flow rates at the downstream camcorders were not used. These matching issues included the unmatched vehicles, or in cases where ramps existed in the work zone, the vehicles entering from the on ramps/exiting to the off ramps that were not recorded.

- **Vehicle Type/Percentage of Trucks.** Three categories of vehicle types (passenger cars, single unit trucks, and truck-trailers) were recorded in the work zones. From the number of single unit trucks and truck-trailers, the percentage of trucks (for that group of vehicles) could be calculated by dividing the number of trucks of the interested category by the total number of vehicles. Please note that truck percentages were also calculated using the traffic information from the first camcorder, regardless of whether it was matched at the downstream camcorders.
- **Time of Day.** Since a time stamp for each vehicle was available, the time of day information was easily obtainable.
- **Passing Maneuvers.** For all of the downstream camcorders (other than the first one), a vehicle ID and an order ID for each vehicle was available. In cases where no ramp existed between a camcorder pair, the difference between the vehicle ID and the order ID was just the overall number of overtaking vehicles (or the number of vehicles being overtaken) for a specific vehicle, over the entire length between the camcorders. Even though more overtaking and being overtaken could happen inside the section, the overall number of vehicles overtaking/being overtaken was felt to be useful information.

However, for cases where ramps existed inside the section, due to on/off ramp traffic, the meaning of this calculated variable was more complicated. Thus, the passing maneuver variable was not utilized.

4.2.4 Extracted Sample Size

Subject to the usable video length and the percentage of matched vehicles, the sample size for each work zone (more specifically, work zone sections) varied. Table 4.4 shows how many vehicles were matched for each section (including work zone sections, advance warning areas, and two downstream sections), which subsequently became our final database.

TABLE 4.4
Summary of Sample Sizes

Section ID	Date	Number of Groups	Total Number of Vehicles
332961	5/16/2011	11	554
332961	5/18/2011	13	646
311041	6/9/2011	12	627
311042	6/9/2011	12	627
311041	7/14/2011	12	635
311042	7/14/2011	12	635
300201	6/21/2011	13	402
300202	6/21/2011	13	638
300201	6/23/2011	14	457
300202	6/23/2011	14	682
301271	7/19/2011	13	642
301271	7/20/2011	13	682
316691	10/21/2011	12	600
316692	10/21/2011	14	700
316691	10/25/2011	14	703
316692	10/25/2011	14	702
341111	11/8/2011	7	350
341112	11/8/2011	7	269
341113	11/11/2011	11	547
341114	11/11/2011	11	530
341115	11/11/2011	11	524
		Total Observations	**12152**

4.2.5 Extracted Police Activities

The police enforcement activities were recorded both by field documentation and with the help of the GPS tracking units. A brief revisit of how the Purdue Research Team planned and coordinated the police enforcement in the work zones is provided below:

- **Planning.** The Purdue Research Team coordinated with the INDOT project engineers (sometimes the contractors as well) to preliminarily set the data collection schedule and to obtain the permission of the project engineers and the contractor to bring the police enforcement and data collection equipment into their work zone. Once their permission was obtained and the schedule was preliminarily set, a tentative enforcement plan was drafted and sent to ISP at least one week in advance of the enforcement dates. In this tentative enforcement plan, the number of police vehicles for each period, the approximate location of the police vehicles, and the proposed strategy were explained in detail. If ISP had no problem sending police officers on the scheduled dates to the selected work zones, and the plan was finalized.
- **Field Coordination.** On the days of enforcement, the Purdue Research Team field crew met the participating ISP officers at an appointed location. The enforcement assignments were briefed to the ISP officers. Also, the GPS tracking unit was distributed to each participating ISP officer to record their locations and, in cases where they had to leave the work zone or carry out a pursuit, to know when they were not at their assigned locations. Finally, in some work zones where the assigned location was not straightforward to find, the Purdue Research Team field crew showed the ISP officers to their locations.

With the enforcement plan, field coordination records, and data extracted from the GPS tracking unit, the police enforcement activities were well documented. The detailed police enforcement activities are shown in Appendix 4 of this report. The difference between the police enforcement activities shown in this section and the police enforcement log shown in the data collection section is that the log shows the activities on a car by car basis, while in this section, the activities are shown on a location basis, which is more oriented for modeling use.

4.2.6 Extracted VMS Information

VMS was used for all of the work zones, except the South Bend work zone where a VMS was not available for our use. The VMSs were dispatched and operated directly by INDOT; therefore, the Purdue Research Team was required only to identify their locations and the planned schedule then was strictly followed with the following two exceptions.

The first exception was in the Tippecanoe work zone, the first site in this experiment. Due to some last minute changes in the plan and inadequate communication between the Purdue Research Team and INDOT, the VMS was located in the wrong direction on the road. The Purdue Research Team identified this issue on the first day of data collection, but it was too late for INDOT to relocate this VMS board that day. Fortunately, the contractor had a VMS at a proper location for our purposes and was willing to let the Purdue Research Team use that VMS board. Therefore, for this work zone, the VMS was off for the first day and on for the second day.

The second exception happened in the Fishers work zone. This time due to apparent miscommunication within INDOT, the VMS board was pulled away during the non-enforcement period of the second day of data collection. Thus, the VMS was recorded as off for the entire PM period of the second day at the Fishers work zone.

On normal data collection days, the VMS followed the schedule shown in Table 4.5.

4.2.7 Summary

With the effort described in this section, a large amount of data collected from the field was extracted, processed, and documented. Although not all possible data were processed and used for analysis (e.g., overtaking and variance of speed), these date are easily accessible for processing and further analysis.

The dataset currently processed by the Purdue Research Team is a very comprehensive one and enabled us to conduct for various analyses.

4.3 Speed Modeling

The work zone sites in this data collection effort formed clusters of observations, and the sampling technique introduced another hierarchy of clusters. Moreover, various interactions (between treatment factors and between treatment factors and blocking factors) were also of great interest in this study. To address the complex data structure, we decided to use the Multilevel Models, also known as Mixed Linear Models, or Hierarchical Linear Models (similar to Random Effect Models), which are suitable for data that exhibit clusters and hierarchies (*47*). Not only is the Multilevel Model capable of accounting for the correlation at each level, it can also incorporate the interactions between levels.

Also, out of the 12,152 observations, the observations in actual work zones were modeled separately as being in advance warning areas or being downstream of work zones. The true effect in work zones therefore was captured. The sample size for the work zone observations was 9,428.

4.3.1 Multilevel Modeling

As previously mentioned, the dataset exhibited multiple levels. The work zone segments formed the top level (level one clusters) with distinctive geometric features and traffic characteristics. Common unknown local conditions introduced dependence to the error term at the segment level, which needed to be accounted for. The most significant concern about this three level structure was that, with only nine work zone segments, the sample size was too small to include any top level variables. The Purdue Research Team tried two distinctive approaches to solve this issue; the first was to use fixed effects to account for the work zone level effect, while the second approach grouped the work zone segments and used interactions between the work zone groups and the lower level variables.

At the second level, the vehicle groups (50 consecutive vehicles in 30-minute intervals subject to the same enforcement strategy and similar traffic conditions) formed another level of clusters. Although the enforcement and traffic volume variables were included in the model, the interactions between the consecutive vehicles and the interruptions from construction activities could not be addressed with fixed effects. Thus, correlation within each vehicle group also needed to be accounted for.

At the third level, individual vehicles were classified as cars (including small pickups, SUVs, and vans); single-unit trucks (SU); or truck-trailer combinations.

The model formulations for the two approaches (model with fixed or random work zone segment effects) are different and are introduced in the following sections.

TABLE 4.5
Experimental Design Matrix for Work Zone Enforcement

Day One	10:00 am–11:30 am	High intensity enforcement	VMS ON
Day One	11:30 am–1:00 pm	High intensity enforcement	VMS OFF
Day One	1:00 pm–2:00 pm	No enforcement	VMS OFF
Day One	2:00 pm–3:30 pm	Low intensity enforcement	VMS OFF
Day One	3:30 pm–5:00 pm	Low intensity enforcement	VMS ON
Day Two	10:00 am–11:30 am	Low intensity enforcement	VMS OFF
Day Two	11:30 am–1:00 pm	Low intensity enforcement	VMS ON
Day Two	1:00 pm–2:00 pm	No enforcement	VMS OFF
Day Two	2:00 pm–3:30 pm	High intensity enforcement	VMS ON
Day Two	3:30 pm–5:00 pm	High intensity enforcement	VMS OFF

4.3.2 Speed Model with Fixed Work Zone Segment Effects

In this model, all of the variables at the two lower levels were included along with their interactions. For the work zone sections, two major issues prevented the use of variables at this level. The first issue was the previously mentioned sample size issue since there were only nine sections with multiple variables. Secondly, most of these variables were highly correlated (e.g., in this sample, urban is perfectly correlated with more than two lanes, bridge project is highly correlated with short length, and speed limit is perfectly correlated with freeway indicator, etc.). Thus, at the top level, rather than using any work zone characteristic variables, fixed effects were used to account for the differences between the different sections.

Interactions between the two lower levels were also included in the model as the hypothesis of the Purdue Research Team was that truck-trailer combinations and single unit trucks may behave differently from passenger cars when police enforcement is present. However, due to the small number of top level observations and the fact that fixed effects other than the variables were used at this level, any interaction with the work zone section level variables were not included in the fixed effect model to preserve the generality.

Finally, the random effects at the vehicle group level were included in this model. As mentioned, there were only nine work zone sections in the dataset. A rule of thumb for using random effects in a multilevel model is that for the top level, around 30 observations will return a desirable asymptotic property, while the "minimum" requirement for using random effects is believed to be 10. In this case, with only nine work zone segments, the use of random effects really pushed the boundaries of this model. Thus, the fixed effect model was also estimated for comparison. The final model formulation is shown below:

$$y_k = X_k \beta + \mu_{jk} + \omega_k,$$

where y_k is the Kth observation of the dependent variable Y, X_k is the vector of the explanatory variables in the k observation, and β is the vector of the fixed effects to be estimated. The fixed effects are included in the X_k and β. The μ_{ik},and ω_k are the error components for the Kth observation, with j denoting the vehicle group cluster and k being the observation index applying to the individual vehicles in the sample. Thus, μ_{ik} is the random effect at the vehicle group level clusters, and $\omega_k$is the unexplained residual. Both error components are assumed to be identically independently distributed (IID) across the observations and each one of them follows a normal distribution, and they are independent from X_k and from each other.

This model was estimated using the Mixed Procedure in SAS, which estimates the multilevel linear models using Restricted Maximum Likelihood methods. Generally, the variables are selected at the 95% significance level, but one exception was allowed (that is still 90% significant), which will be explained in the interpretation section.

The model output (Figure 4.10) shows that 9,424 observations were used in this model, and there were 147 vehicle groups in the dataset. Two covariance parameters were included in the model, which are the vehicle groups and the residuals. The model converged successfully.

The covariance estimation table shows that the Vehicle Group Random Effect accounted for almost 30% of the residual in the model, which was 7.77% of the total variance in the dependence variable (Table 4.6). These statistics suggest that the addition of this random effect significantly improved the estimation.

4.3.3 Speed Model with Random Work Zone Segment Effects

To better understand how various work zone features affect the selection of speed in work zone sections, a model was estimated with the work zone characteristics variable and the interaction between the work zone segment and the lower level variables. In this model, the work zone sections were categorized into groups with distinct features. However, the method used for work zone categorization here was not the most desirable due to the availability of (or the lack of) appropriate work zones for the data collection so the limitations of our categorization method is duly noted. The paradox faced by the Purdue Research Team was that if we made good use of the many work zone features variables available, the categorization most likely would end up with one or two sections in each category; but if a more parsimonious categorization method was adopted, over-generalization was unavoidable. Ultimately, after in-depth investigation of the behavior in each work zone section, the following conclusions were made based on the available data:

- Speeds did not vary much between rural and urban sections, with everything else being equal.
- Speeds were significantly lower when major ramps from system interchanges and significant curves were present, regardless of the presence of police enforcement.
- Speeds were significantly lower and much less sensitive to police enforcement when there was only one lane open to traffic in one direction.
- Speeds in non-freeway work zones were significantly slower than in freeway work zones, which was expected, and the effect of police enforcement also was not as strong.

Based on these findings, the Purdue Research Team categorized all of the highway work zones according to Figure 4.11.

While the nine work zone sections did not cover all six categories, the following four categories were included in the sample:

1. **Work Zone Category_1.** Multilane freeway work zone sections without system interchanges. This category includes freeway work zone sections without major

```
The Mixed Procedure
Dimensions
Covariance Parameters            2
Columns in X                    24
Columns in Z                   147
Subjects                         1
Max Obs Per Subject           9428

Number of Observations
Number of Observations Read            9428
Number of Observations Used            9424
Number of Observations Not Used           4

Covariance Parameter Estimates
Cov Parm     Estimate
IDGroup        4.8450
Residual      11.3188

Fit Statistics
-2 Res Log Likelihood         50075.5
AIC (smaller is better)       50079.5
AICC (smaller is better)      50079.5
BIC (smaller is better)       50085.5

Solution for Fixed Effects
Effect             Estimate       STDEV      DF    t Value    Pr > |t|
Sect300201          48.4342      0.6833    9263      70.89      <.0001
Sect300202          58.5311      0.7368    9263      79.44      <.0001
Sect301271          42.0550      0.5073    9263      82.89      <.0001
Sect311041          59.9709      0.5280    9263     113.58      <.0001
Sect311042          59.1212      0.4862    9263     121.61      <.0001
Sect332961          58.9708      0.7645    9263      77.14      <.0001
Sect316692          50.6208      0.5864    9263      86.33      <.0001
Sect341112          47.2485      0.8938    9263      52.86      <.0001
Sect341114          47.3942      0.7709    9263      61.48      <.0001
hour0910            -1.4080      0.4890    9263      -2.88      0.0040
vol1012             -1.6618      0.6314    9263      -2.63      0.0085
vol12plus           -2.7185      0.6908    9263      -3.94      <.0001
VMS01               -3.4957      0.9277    9263      -3.77      0.0002
ADV0005             -1.7432      0.2909    9263      -5.99      <.0001
ADV0510             -1.6860      0.3188    9263      -5.29      <.0001
NumSecBgn           -2.5695      0.3536    9263      -7.27      <.0001
PCsecin             -2.9988      0.4194    9263      -7.15      <.0001
SU                  -2.5957      0.2156    9263     -12.04      <.0001
NumSecBgn*SU         0.5490      0.3187    9263       1.72      0.0849
SU*PCInSec1          1.8388      0.8330    9263       2.21      0.0273
Semi                -2.5896      0.1201    9263     -21.57      <.0001
VMS01*Semi          -0.8776      0.3341    9263      -2.63      0.0086
NumSecBgn*Semi       0.7638      0.2030    9263       3.76      0.0002
PCInSec1*Semi        1.7210      0.4476    9263       3.84      0.0001
```

Figure 4.10 SAS output of the speed model with fixed effects.

ramps from/to system interchanges or significant curvatures, with at least two lanes open in one direction, and with a 45 mph speed limit.

2. **Work Zone Category_2.** Multilane freeway work zone sections with system interchanges. This category includes freeway work zone sections with major ramps from/to system interchanges, with curvature or other features that affect speed, and with a 45 mph speed limit.
3. **Work Zone Category_3.** Non-freeway work zone sections. This category includes work zone sections on non-freeway facilities and usually has intersections with minor roads and a 35 mph speed limit.
4. **Work Zone Category_4.** Single-lane freeway work zone sections without system interchanges. This category includes freeway work zone sections with lane closure to only one lane each direction, without major ramps from/to system interchanges, and with a 45 mph speed limit.

Out of the nine work zone sections, five fit into Work Zone Category_1, which would be considered as the "baseline" work zone type. Two work zone sections, both from the Terre Haute work zone, fit into Work Zone Category_4. One work zone section from the

TABLE 4.6
Covariance Estimation in Multilevel Model (Fixed Effect Model)

Covariance Parameter	Estimate	Percent of Residual	Percent of Total Variance
Vehicle group	4.845	29.97%	7.77%
Residual	11.3188	70.03%	18.15%

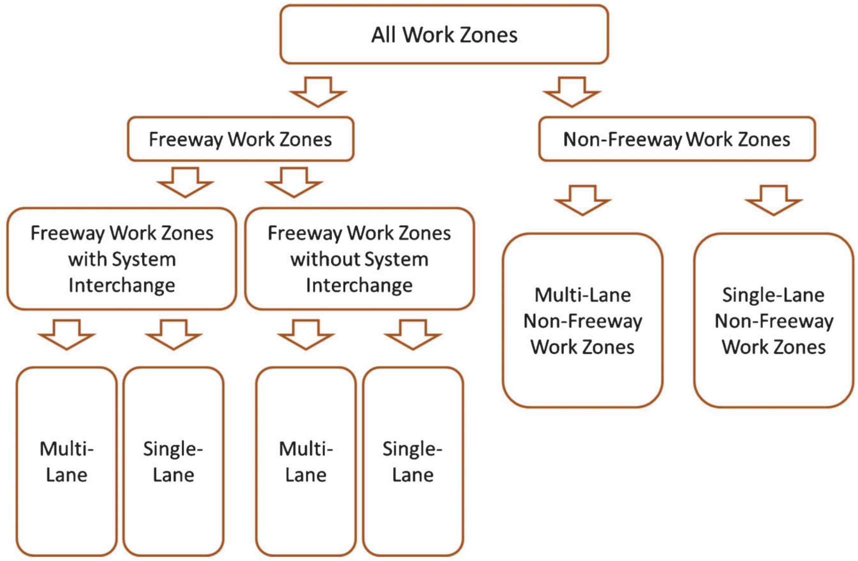

Figure 4.11 Categorization of all work zones.

Airport work zone fit into Work Zone Category_2; and finally, the South Bend work zone fit into Work Zone Category_3.

With this categorization, the random effect model was estimated. The work zone categories were used as fixed effects instead of individual work zone section fixed effects. Also, the interactions between the work zone categories and all of the lower level variables were used. Random effects both at the work zone section level and the vehicle group level were incorporated to control for correlation. The model formulation is shown below:

$$y_k = X_k \beta + \mu_{ik} + \varphi_{jk} + \omega_k,$$

where y_k is the Kth observation of the dependent variable Y, X_k is the vector of the explanatory variables in the k observation, and β is the vector of the fixed effects to be estimated. The μ_{ik}, φ_{jk}, and ω_k are the error components for the Kth observation, with i denoting the work zone segment cluster, j being each vehicle group cluster, and k being the observation index applying to the individual vehicles in the sample. Thus, μ_{ik} and φ_{jk} are the random effects at the two levels of clusters, and $\omega_k$is the unexplained residual. All three error components are assumed to be identically independently distributed (IID) across the observations and each to follow a normal distribution, which are independent from X_k and from each other. The sample size (nine segments) at the top level could have been an issue for using the random effect model, but as the covariance estimation suggests, there was substantial interclass correlation and thus the random effect was kept.

The output of the best fitted model is shown in Figure 4.12.

From the model output, it can be seen that all lower level (traffic, enforcement, vehicle type) variables were replaced with their interactions with the work zone category indicators. Also, the overall model fitting was significantly improved (Log-Likelihood improved from 50060.1 to 49845.6) with the same number of explanatory variables (24 in both cases). Also, as shown in the covariance estimation table, the Work Zone Segment Random Effect accounted for 43.46% unexplained residual, which was a 19.84 total variance of the dependent variable.

This table suggests that the categorization employed by the Purdue Research Team successfully captured many of the differences among the different work zone sections, and the addition of the work zone segment level random effect brought significant improvements when compared to the fixed effect model. The model interpretation and the enforcement recommendation therefore was based on the random effect model.

4.3.4 Model Output and Interpretation

Based on the random effect model, the segment and vehicle group random effects accounted for 43.46% and 17.87% of the unexplained variance in the data, respectively; and, together, they accounted for 28% of the total variance (Table 4.7). This result shows the necessity of accounting for the heterogeneity in analyzing such clustered data and confirmed once more the huge site differences, even when interactions were used. The coefficient estimations of the final model, using all interactions, are shown in Table 4.8.

A total of 9,824 observations were used in the final model. As mentioned previously, Work Zone Category_1 (multilane freeway work zones without system interchange ramps) had the largest number of observations

```
The Mixed Procedure

Dimensions
Covariance Parameters             3
Columns in X                     24
Columns in Z                    156
Subjects                          1
Max Obs Per Subject            9428

Number of Observations
Number of Observations Read            9428
Number of Observations Used            9424
Number of Observations Not Used           4

Covariance Parameter Estimates
Cov Parm     Estimate
IDGroup        5.0900
IDSect        12.3762
Residual      11.0096

Fit Statistics
-2 Res Log Likelihood        49845.6
AIC (smaller is better)      49851.6
AICC (smaller is better)     49851.6
BIC (smaller is better)      49860.5

Solution for Fixed Effects
Effect                  Estimate       STDEV      DF    t Value    Pr > |t|
WZ_cat1                  57.2133      1.6088    9259      35.56      <.0001
WZ_cat1*NumSecBgn        -3.2780      0.4609    9259      -7.11      <.0001
WZ_cat1*ADV0005          -1.9677      0.2941    9259      -6.69      <.0001
WZ_cat1*PCsecin          -2.4669      0.5195    9259      -4.75      <.0001
WZ_cat1*VMS01            -3.6079      0.9474    9259      -3.81      0.0001
WZ_cat1*VMS45             0.7514      0.2692    9259       2.79      0.0053
WZ_cat1*hour0910         -0.8537      0.3549    9259      -2.41      0.0162
WZ_cat1*vol08plus        -1.1751      0.2738    9259      -4.29      <.0001
WZ_cat1*truck            -2.6731      0.1158    9259     -23.08      <.0001
WZ_cat1*PCsecin*Semi     -1.1459      0.2555    9259      -4.49      <.0001
WZ_cat1*NumSecB*Semi      0.8321      0.2459    9259       3.38      0.0007
WZ_cat1*VMS01*truck       0.9238      0.3510    9259       2.63      0.0085
WZ_cat2                  45.3664      3.5523    9259      12.77      <.0001
NumSecBgn*WZ_cat2        -0.7275      0.4582    9259      -1.59      0.1123
truck*WZ_cat2            -2.1773      0.2662    9259      -8.18      <.0001
WZ_cat3                  40.9667      3.6205    9259      11.32      <.0001
WZ_cat3*SumPC            -2.0376      0.7011    9259      -2.91      0.0037
Semi*WZ_cat3             -1.6049      0.3908    9259      -4.11      <.0001
WZ_cat3*SU               -2.7568      0.7298    9259      -3.78      0.0002
Semi*WZ_cat3*NumSecI      1.7371      0.6831    9259       2.54      0.0110
WZ_cat3*SumPC*SU          1.0847      0.6080    9259       1.78      0.0745
WZ_cat4                  44.8254      2.6185    9259      17.12      <.0001
NumSecBgn*WZ_cat4        -2.1957      1.4016    9259      -1.57      0.1173
WZ_cat4*VMSIn            -3.5701      1.4827    9259      -2.41      0.0161
```

Figure 4.12 SAS output of the speed model with random effects.

TABLE 4.7
Covariance Estimation in Multilevel Model (Random Effect Model)

Covariance Parameter	Estimate	Percent of Residual	Percent of Total Variance
Work zone segment	12.3762	43.46%	19.84%
Vehicle group	5.09	17.87%	8.16%
Residual	11.0096	38.66%	17.65%

TABLE 4.8
Parameter Estimation in Multilevel Model

Variable	Estimate	Standard Deviation	t Value
Work Zone Category-1 (Multi-lane freeway without system interchange) 45 MPH Speed Limit			
Intercept	57.213	1.609	35.56
PEV at beginning	-3.278	0.461	-7.11
PEV within half mile upstream	-1.968	0.294	-6.69
PEV inside segment	-2.467	0.520	-4.75
VMS within one mile upstream	-3.608	0.947	-3.81
VMS 4–5 miles upstream	0.751	0.269	2.79
Morning (9:00 am to 10:00 am)	-0.854	0.355	-2.41
High volume (>800 v/(lane × hr))	-1.175	0.274	-4.29
Truck (SU truck or truck trailer)	-2.673	0.116	-23.08
PEV inside × truck trailer	-1.146	0.256	-4.49
PEV at beginning × truck trailer	0.832	0.246	3.38
VMS within one mile upstream	0.924	0.351	2.63
Truck (SU truck or truck trailer)			
Work Zone Category-2 (Multi-lane freeway with system interchange) 45 MPH Speed Limit			
Intercept	45.366	3.552	12.77
PEV at beginning	-0.728	0.458	-1.59
Truck (SU truck or truck trailer)	-2.177	0.266	-8.18
Work Zone Category-3 (Single-lane non-freeway) 35 MPH Speed Limit			
Intercept	40.967	3.621	11.32
Number of police enforcement vehicles (0, 1, or 2)	-2.038	0.701	-2.91
Truck trailer	-1.605	0.391	-4.11
Single-unit (SU) truck	-2.757	0.730	-3.78
PEV inside segment × truck trailer	1.737	0.683	2.54
Each PEV × SU truck	1.085	0.608	1.78
Work Zone Category-4 (Single-lane freeway without system interchange) 45 MPH Speed Limit			
Intercept	44.825	2.619	17.12
PEV at beginning	-2.196	1.402	-1.57
VMS inside segment	-3.570	1.483	-2.41

and, consequently, most of the variables included in the final model describe this work zone category.

In Work Zone Category_1, the significant Morning variable indicates that the average speed was 0.854 mph lower between 9:00 am and 10:00 am. The High volume variable indicates an average speed reduction of 1.175 mph in vehicle flows with a traffic rate higher than 800 veh/(lane • hour). This finding is consistent with previous studies; namely, Benekohal et al. (*20*) used 720 veh/(lane • hour) and Hauer et al. (*35*) used 900 veh/(lane • hour) as their criteria to sample free-flow vehicles. In our study, speeds measured during traffic congestion were excluded from the analysis.

All of the intercepts and speed reductions attributed to police enforcement and estimated from the obtained model are summarized in Table 4.9. They are listed by work zone and vehicle category.

In multilane freeway work zones without system interchanges (Category 1), the average speed of cars was 57.21 mph when no enforcement was present. SU trucks and truck-trailers moved at an average speed of 54.54 (no significant difference between the two categories was found). With the posted speed limit for all sites being 45 mph, speeding was found to be a serious issue in these freeway work zones (four rural and one urban).

The effects of police enforcement vehicles (PEV) positioned at three different locations in relation to the work zone segment where the average speeds were measured (beginning, inside, and end). These segments corresponded with the work zone segments, but they were not always identical to the work zone segments. The length of the speed measurement segments varied from 0.6 to five miles with most of the lengths between one and three miles. As expected, we found that the most effective enforcement strategy for speed reduction was positioning a PEV at the beginning of the segment (average speed reduction of 3.28 mph for cars and SU trucks and 2.45 mph for truck-trailers). Stationary police enforcement within the segment reduced the average speed of cars and SU tracks by 2.47 mph and of truck-trailers by 3.61 mph. Positioning a PEV upstream of the speed measurement segment (about .5 mile) was found to reduce the average speed by 1.97 mph

TABLE 4.9
Summary of Speed Reduction Estimated with the Multilevel Model

Vehicle Type	No Enforcement	PEV at Beginning	PEV Inside	PEV at End	PEV Upstream	VMS01
Multi-Lane Freeway Work Zone without System Interchange (Category 1)						
Cars	57.21	-3.28	-2.47	N/S	-1.97	-3.61
SU	54.54	-3.28	-2.47	N/S	-1.97	-2.68
Truck trailer	54.54	-2.45	-3.61	N/S	-1.97	-2.68
Multi-Lane Freeway Work Zone with System Interchange (Category 2)						
Cars	45.37	-0.73	N/A	N/S	N/A	N/A
SU	43.19	-0.73	N/A	N/S	N/A	N/A
Truck trailer	43.19	-0.73	N/A	N/S	N/A	N/A
Non-Freeway Work Zone (Category 3)						
Cars	40.97	-2.04	-2.04	N/A	N/A	N/A
SU	38.21	-0.95	-0.95	N/A	N/A	N/A
Truck trailer	39.36	-2.04	-0.30	N/A	N/A	N/A
Single-Lane Freeway Work Zone without System Interchange (Category 4)						
Cars	44.83	-2.20	N/S	N/S	N/S	-3.57
SU	44.83	-2.20	N/S	N/S	N/S	-3.57
Truck trailer	44.83	-2.20	N/S	N/S	N/S	-3.57

N/A = strategy not available from experiment.
N/S = variable not significant in the model.

regardless of the vehicle type. This last finding is consistent with previous studies, indicating that the effect of police enforcement vanishes quickly downstream and enforcement a short distance upstream is expected to be less effective. One would expect the effectiveness of police enforcement inside the segment to depend on its relative location (near the beginning, halfway, near the end); but this factor was not found to be significant, probably due to the lack of variability in the data. These effects were estimated with the assumption that if more PEVs are used in a work zone, the effects would add up. As many as four police vehicles were present in longer work zones and as many as two in shorter work zones.

An interesting and useful finding of this study pertains to the effectiveness of VMS. VMS which displays enforcement messages placed within one mile upstream of the segment with police enforcement was found to further reduce the speed of cars by 3.61 mph and trucks by 2.68. This speed reduction, stronger than the effect of a single police vehicle, added to the effect of the police enforcement. VMS displaying enforcement messages was used only where police officers were actively enforcing the speed limit in order to preserve the drivers' perception of the VMS message as being true. Otherwise, gradual deterioration of the VMS effect might occur.

VMS displaying enforcement messages had a significant effect on speed up to one mile downstream as opposed to one-half mile for the police enforcement, which might suggest that the effectiveness of VMS deteriorates slower than does police enforcement. On the other hand, VMS displaying enforcement messages placed further away from the segment showed no significant speed reduction effect, while those "too far away" (four to five miles upstream) were found to be associated with a speed increase in the work zone. This increase could have been caused by confounding factors or by the "rebounding" effect. Some drivers, in order to compensate for an earlier speed reduction, might speed up after driving four to five miles without seeing police enforcement. No interaction was found between the VMS and the intensity of the enforcement.

The other work zone categories had much smaller numbers of observations collected at one or two sites. Furthermore, the model indicates that speeding was not as serious an issue in these types of work zones as it was in the work zones of Category 1 (at least during our data collection); thus, the reduction in speed in response to the police enforcement could not be expected to be as strong. Generally, the findings from these work zones are consistent with those from the first category, including the enforcement at the beginning of the segment and VMS effective at the sites had we been able to check this effect. VMS was not available for Category 3, and it was placed more than one mile upstream of the Category 2 work zone.

Police enforcement was found to be statistically significant in the non-freeway work zones. However, this effectiveness was similar for different placements of police vehicles. This work zone was short (0.63 mile) compared to the other categories, and the position of the police vehicles therefore may not have had as pronounced effect as in longer work zones. The speed reduction in this work zone was somewhat smaller than at other sites as well. One possible explanation was that the vehicles were already traveling at a lower speed due to the non-freeway conditions and the single traffic lane

Effect	Estimate	STDEV	DF	t Value	Pr > |t|
Intercept	65.7068	1.6372	22	40.13	<.0001
SU	-3.6102	0.8899	1271	-4.06	<.0001
Semi	-5.6635	0.6869	1271	-8.24	<.0001
PM13	4.9312	1.9912	1271	2.48	0.0134
VMS01	-5.4698	2.1388	1271	-2.56	0.0107
Semi*VMS01	3.1193	1.1562	1271	2.70	0.0071
NumSecBgn	-8.4099	2.1683	1271	-3.88	0.0001
Semi*NumSecBgn	2.2731	1.2081	1271	1.88	0.0601

Solution for Fixed Effects

Figure 4.13 SAS output of the speed model for section 316691.

and the lack of opportunity for passing. A similar explanation could be the lack of an effect of additional enforcement inside the single-lane freeway work zone.

4.3.5 Speed Models for Non Work Zone Sections

During the data collection, the Purdue Research Team have also measured speed in several non-work zone sections to provide additional insight about the effectiveness of police enforcement upstream and downstream of the work zone. For the only section downstream of the work zone, no enforcement strategy was found to affect the speed, thus, only the models for the three upstream sections were shown here.

The model output for Section 316691 is shown in Figure 4.13, which is the advance warning area for a Category 1 work zone. All of the signs make sense. For the variables that were not included in the model, the enforcement at the end of the section (in this case, the police vehicle at the end of this section is at the beginning of the actual work zone) was not found to be significant. The traffic flow rate (volume per lane) was also insignificant.

In this sub-dataset, there was no observation in the morning period without enforcement. In the noon non-enforcement period, the average speed was slightly above 70 mph (Intercept + PM). Single unit trucks on average were 3.61 mph slower than passenger vehicles, while truck-trailers on average were 5.66 mph slower. The speed reduction effectiveness of the police vehicle at the beginning of this section was 8.41 mph for passenger cars and single unit trucks, and 6.14 mph for truck-trailers, even though this section is not in the work zone yet and the speed limit is 70 mph. When VMS was on and displaying the enforcement messages, there was a 5.47 mph speed reduction observed for passenger cars and single unit trucks, and 2.35 mph for truck-trailers. Even though the magnitude of the speed reduction effect appeared to be too dramatic, the findings were very consistent with the field observations. It was observed from the field that, when police enforcement was present, a lot of drivers saw the warning signs saying “45 MPH AHEAD” and perceived these signs as the speed limit and slowed down. Thus, when a police vehicle was present at this advance warning section and when the VMS was showing enforcement messages, the drivers may have reacted to such enforcement by reducing their speed to 45 mph even before they reached the actual work zone.

The model output for Section 341111 is shown in Figure 4.14, which is the advance warning area for a Category 4 work zone. Again, the signs make intuitive sense. The speeds for all three types of vehicles exceeded the legal speed limit when police enforcement was not present. The afternoon indicator PM14 shows a reduction of speed after 1400 hours, which is opposite to the findings from the work zone sections. The Purdue Research Team noticed that there were only 37 observations after 1400 hours since the Purdue Research Team arbitrarily discarded the data when they believed congestion was present. These 37 observations after 1400 hours could also have been affected by the higher traffic volume, which was not accounted for by the volume per lane variable so no inference could be made about this variable. For the VMS displaying enforcement messages, also due to the discarded data caused by congestion, only 50 observations were available with a VMS displaying an enforcement message, which were the first 50 observations of the day. Thus, both the PM14 and VMS5Plus indicators were treated with caution.

The model output for Section 341113 is shown in Figure 4.15, which is the advance warning area for a

Solution for Fixed Effects

Effect	Estimate	STDEV	DF	t Value	Pr > |t|
Intercept	76.6631	3.8715	4	19.80	<.0001
SU	-3.4102	0.9158	340	-3.72	0.0002
Semi	-4.2829	0.4114	340	-10.41	<.0001
pm14	-3.0585	1.1607	340	-2.63	0.0088
VolPerLane	-0.03232	0.008545	340	-3.78	0.0002
VMS5Plus	-4.4603	2.1551	340	-2.07	0.0392

Figure 4.14 SAS output of the speed model for section 341111.

Effect	Estimate	STDEV	DF	t Value	Pr > |t|
Intercept	64.4310	0.8233	7	78.26	<.0001
SU	-2.9759	1.1797	533	-2.52	0.0119
Semi	-4.9066	0.4963	533	-9.89	<.0001
pm15	-8.2176	2.2956	533	-3.58	0.0004
NumSecIn	-9.7219	1.0895	533	-8.92	<.0001
NumSecEnd	-7.1235	1.8311	533	-3.89	0.0001
Semi*NumSecEnd	3.5855	1.1205	533	3.20	0.0015

Solution for Fixed Effects

Figure 4.15 SAS output of the speed model for section 341113.

Category 4 work zone. Again, the signs all make intuitive sense. In this case, the speeds for three types of vehicles are all different, and all of them are below the legal speed limit for non-work zone sections. PM15 shows a very strong effect, which suffers the same issues as the PM14 in the previous section, with only 49 observations after deleting the congested period. Thus, the effect of PM15 was treated with caution and no inference could be made. The two enforcement variables were very significant with one showing an almost 10 mph speed reduction and even the police car at the end of section showed a more than 7 mph speed reduction. Again, this section is the advance warning area, which has been shown before to have a pronounced effect in speed reduction. However, in this case, truck-trailers were found to be less affected by enforcement. This effect was expected because when vehicles were in the lane closure section, they were expected to be traveling at the same speed so the originally slower truck-trailers did not need to reduce their speed as much as other vehicles.

4.3.6 Summary for Work Zone Categories

With the model output interpreted above, a summary follows of what has been learned about each type of work zone. The basic principles are made according to the model outputs. For further detail unavailable from the model, our knowledge from the literature, field observations, and other sources were used to make reasonable assumptions.

Multi-Lane freeway work zone without system interchange (Category 1). First of all, the speeds in these work zones were seriously higher than the legal speed limit, and police enforcement was expected to have significant effect on speed reduction. Since all of the enforcement strategies were significant in the model for this work zone category, all of the conclusions made here are based on the model outcome:

- Stationary police enforcement was effective at the beginning of work zone section (3.28/3.28/2.45).
- VMS displaying enforcement messages within one mile upstream of the work zone section was also very effective (3.61/2.68/2.68).
- Stationary police enforcement inside the work zone section was less effective (2.47/2.47/3.61).
- Stationary police enforcement within one-half mile upstream of the work zone section was the least effective for this work zone category (1.97/1.97/1.97).
- The effectiveness of stationary enforcement or VMS displaying enforcement messages further away upstream was found to be not significant in the model.
- The effectiveness of more than one stationary police vehicles inside the work zones was found to be not significant in the model.
- The effectiveness of police patrolling in the work zone was found to be insignificant (with a small sample size in only one work zone).

Based on these findings from the model, the following general conclusions are made for Work Zone Category 1:

- Enforcement should not be placed more than one-half mile upstream of the work zone beginning.
- VMS displaying enforcement messages should not be placed more than one mile upstream of the work zone beginning.
- The most effective enforcement strategies are stationary enforcement at the beginning of work zone, and VMS displaying enforcement messages, with both showing very similar effectiveness.
- VMS should be used to display enforcement messages whenever available, and should only display enforcement messages when enforcement is in progress.
- Stationary enforcement inside the work zone is less effective and should be used only when enforcement at the beginning of work zone is already being used.
- No more than one police vehicle should be enforcing inside the work zone unless the work zone is very long (threshold estimated in a later section) or they have separate construction areas.
- Stationary police enforcement upstream of work zones will cause additional delays before the work zone and has limited effectiveness inside the work zone and therefore is not recommended.
- All other strategies failed to show a statistically significant effect and thus are not recommended.

Multi-Lane freeway work zone with system interchange (Category 2). Category 2 work zones are less likely to have excessive speeding compared to multi-lane freeway work zones without system interchanges due to the weaving traffic and perhaps also the challenging geometry. As noted in the model interpretation section, the effectiveness of stationary enforcement is not as strong. Conclusions from the model about the effectiveness of the enforcement strategies are shown below:

- Stationary police enforcement at the beginning of a work zone section reduced the speed by 0.73 mph.
- VMS displaying enforcement messages located almost two miles upstream of the work zone was not effective.
- Stationary police enforcement at the end of work zone section is not effective.

Based on these conclusions from the model and with the assumptions made by the Purdue Research Team, the following general conclusions are made for Work Zone Category 2:

- VMS displaying enforcement messages located more than one mile upstream of the work zone is not effective.
- Stationary police enforcement is effective at the beginning of the work zone section.
- When an on-ramp is close to the beginning of the work zone section, and the on-ramp traffic is heavy, stationary police enforcement could be put at the merging point in order to provide a smoother merging. The effectiveness of such enforcement is assumed to be 0.5 mph based on the findings from the other categories.
- VMS displaying enforcement messages within one mile upstream is expected to be effective in speed reduction, and the effect is assumed to be 0.7 mph.

Non-Freeway work zone (Category 3). Unlike the previous category, the speed in the non-access controlled work zone is significantly higher than the legal speed limit. Thus, police enforcement is expected to be relatively effective in such work zones. Though only two enforcement strategies were used in this category of work zone, they were both significant in the model:

- Stationary police enforcement at the beginning of the work zone section was effective (2.04/0.95/2.04).
- Stationary police enforcement inside the work zone section was effective (2.04/0.95/0.30).

However, the very promising strategy of VMS was not used to display enforcement messages for this work zone during the experiment so the conclusions about this category of work zones will be based on the previous categories' findings from the model. The effectiveness of VMS displaying enforcement messages was assumed to be a 2 mph speed reduction across all types of vehicle based on the findings from the other categories. Also, since the work zone was very short, it was unknown whether the effectiveness of stationary police enforcement would vary significantly across locations. No assumptions will be made here about its effectiveness, but when recommending enforcement strategy, the enforcement at the beginning of work zone should always have priority. The conclusions about the work zones in Category 3 are:

- Stationary police enforcement is effective both at the beginning and inside the work zone section.
- The effectiveness of stationary enforcement is not significantly different for the two locations (beginning and mid-point) for short work zones; but for longer work zones, it is expected that enforcement at the beginning of the work zone will yield better results.
- VMS displaying enforcement messages is expected to have a significant effect for this category of work zones when a 2 mph speed reduction is assumed based on the results of other categories.

Single-Lane freeway work zone without system interchange (Category 4). Due to the nature of such work zone sections, the speed in these work zone sections were found to be not significantly different from the legal speed limit, most likely due to the lack of opportunities for drivers to participate in overtaking maneuvers. Thus, police enforcement was not expected to have effectiveness on the magnitude of the other categories of work zones. The findings from the model are summarized below:

- Stationary police enforcement at the beginning of the work zone section was effective (2.20/2.20/2.20).
- VMS displaying enforcement messages inside the work zone section was more effective than enforcement alone (3.57/3.57/3.57).
- All other enforcement variables were not significant in this type of work zone.

It should be noted that, even though all of the enforcement strategies were available to us for this project and were used in the two work zone sections of this category, only two of them were significant in terms of speed reduction. Also, no differences were found among the speeds of the three vehicle types, which also was expected due to the nature of the work zone. Thus, the conclusions for this type of work zone are as follows:

- Stationary police enforcement is effective at the beginning of the work zone section.
- VMS displaying enforcement messages is also effective, even when it is located inside the work zone section.
- Enforcement should not be used upstream of the work zone since its effectiveness is insignificant inside the work zone and will cause additional delays outside the work zone.
- Enforcement inside the work zone is also insignificant provided that there is enforcement at the beginning of the work zone.

4.4 Speed Rebound Model

In the previous model, drivers' speed choices in work zones were estimated under various police enforcement scenarios. However, the model specification relied on a very important assumption on drivers' behavior in regard to police enforcement, namely, that for each enforcement unit (e.g., police car, VMS board) present in the work zone, drivers will lower their speed by a certain extent and keep that speed throughout the work zone. This model specification made it quite convenient to investigate the difference in effectiveness among various police enforcement strategies (e.g., different locations for stationary police cars), but we lacked the ability to estimate the effective distance of each enforcement unit. Moreover, the literature universally has found that the spatial residual effect of police enforcement is very weak, thereby supposing that this underlying assumption of the model specification might not be valid. Thus, an alternative modeling strategy was taken to investigate the effective distance and the validity of the assumption.

From the literature, it is known that the effectiveness of police enforcement deteriorates quickly, or in other words, the speed rebounds quickly over distance. While a limited number of researchers specifically studied this rebound phenomena, one study (*22*) pointed out that there was significant effectiveness 0.2 mile downstream of the enforcement location (without providing the effectiveness at the location for comparison); and another study (*23*) showed there was no residual effect of police enforcement 1.5 miles downstream of the enforcement location. In this study, while from the modeling we found that stationary police enforcement within one-half mile upstream of the work zone had a significant effect on speed reduction, more than one-half mile upstream no significant effect was found. While this finding sheds some light on the problem of interest, empirical evidence is clearly not sufficient to draw any useful conclusion.

Thus, an effort was taken by the Purdue Research Team to investigate the effective distance of police enforcement in work zones. An alternative assumption regarding drivers' behavior was made, and a transformed enforcement variable was created for modeling. The modeling structure was kept to allow differences within different work zone categories and vehicle classes.

4.4.1 Speed Rebound Model Formulation

The alternative assumption made was that while driving in a work zone, drivers will decelerate upon seeing police enforcement and will pick up speed once they have passed the enforcement unit. The basis of this assumption is that drivers only slow down when the threat is imminent and will speed up again once the threat is cleared.

With this assumption, a Speed Rebound Model of the effectiveness of police enforcement was formulated. This model represents how the effectiveness of police enforcement slips away once drivers have a choice of speed in work zones. This model was calibrated using the same data collected from the work zones. To enable the calibration of the Speed Rebound Model, several assumptions were made:

- The desired speed of drivers is always higher than the legal speed limit.
- Drivers reduce their speed choice to a perceived safe speed when they see police enforcement.
- The speed reduction happens quickly and the distance required is neglected.
- The speed is reduced to its lowest level at the location of police enforcement.
- Drivers start to pick up speed immediately after they pass the enforcement.
- The speed rebounds at a constant rate (across distance).
- Drivers will regain their desired speeds and stay at that speed thereafter.

The Speed Rebound Model is illustrated in Figure 4.16.

In this illustration, the X-Axis is the distance, with the Y-Axis being the speed. The vertical yellow bars represent the camera pair, which defined the region of the data collection. The red dashed line represents the "Desired Speed" of a driver (V_D), which is the speed chosen by drivers when enforcement is not present; the green dashed line is the "Perceived Safe Speed" (V_S) of drivers when police enforcement is present. The solid black line denotes the actual speed of the driver (with its average being V_A throughout the data collection segment). As is obvious from the illustration, drivers maintain a relatively high speed (presumably above the legal speed limit) before seeing the police enforcement; and upon seeing it, reduce their speed to their perceived safe speed. Once they have passed the police

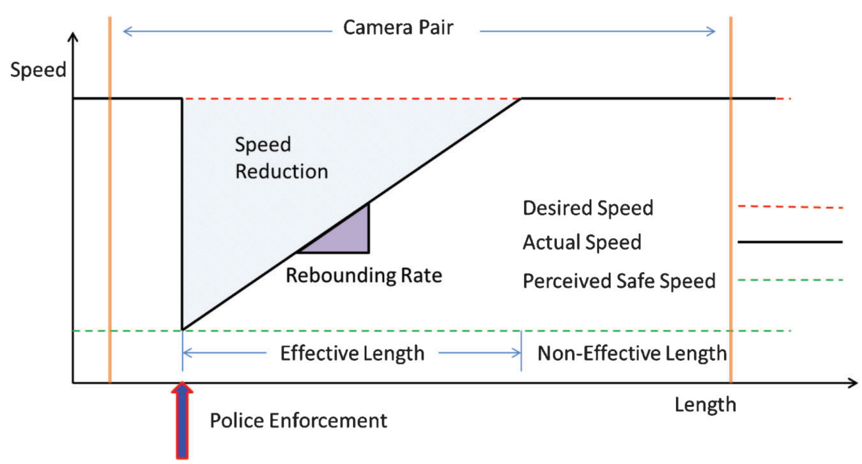

Figure 4.16 Illustration of effective enforcement length.

TABLE 4.10
Variables for Speed Rebound Model

Variable Name	Variable
V_D	Desired speed of drivers
V_S	Perceived safe speed of drivers
V_A	Average speed through the segment
R_R	Rebounding rate of speed
L_E	Effective length of police enforcement
Dist	Distance between the camera pair
EEE	Enforcement effectiveness equivalent

enforcement, drivers start to pick up speed, at a certain rate, which is referred to as the "Rebounding Rate" (R_R) here, until their desired speed (V_D) is reached. The length it takes to regain the desired speed is referred to as the "Effective Length" (L_E) of police enforcement. Table 4.10 shows the denotation of all of these variables, which were used later to derive the model.

In the Speed Rebound Model, there are several known and unknown parameters. Among the known variables, a driver's desired speed (V_D) is the speed chosen by the drivers when enforcement is not present, which corresponds to the intercept in the Speed Model (when all enforcement variables are specified). The speed change ($\overline{\Delta V}$, or $V_D - V_A$) is the difference between the speed when police enforcement is present and absent, which corresponds to the coefficient of the corresponding police enforcement in the model. Among the unknowns, there are a driver's perceived safe speed (V_S), the rebounding rate (R_R), and the effective length of police enforcement (L_E). According to the assumption, these three variables have the following relationship:

$$(V_D - V_S) = R_R * L_E$$

$$\overline{\Delta V} = V_D - V_A = \frac{L_E * (Rr * L_E)/2}{Dist} = \frac{Rr * L_E^2}{2 * Dist}$$

The first equation is straightforward enough, that the absolute value of the speed reduction (or rebound) is equal to the rebounding rate multiplied by the effective length (which is also the rebounding length). The second equation shows how the effectiveness of speed reduction within the effective length is averaged over the entire length of the data collection segment, with the left hand side being the change in average speed (model coefficient) and the right hand side being the area under the dashed red line (desired speed) and above the solid black line (actual speed) over the length of the data collection segment.

There are more unknowns than equations, thus, assumptions were made about one of these unknowns and the models were estimated to determine the best value of it.

Even though assumptions and simplifications are made, considering the data availability and the purpose of this model, this Speed Rebound Model is believed to reasonably represent driver behavior in the presence of police enforcement. The calculations and calibrations are shown below.

4.4.2 Variable Transformation

With this new assumption on driver behavior, the Speed Rebound Model of police enforcement effectiveness was calibrated using the same data which facilitated the speed model. The concept is shown below:

- Exhaustive assumptions were made about the effective length of police enforcement in work zones.
- Transformations were made on the variables in the Speed Rebound Model.
- The transformed variables were entered in the speed model.
- The best assumed value of the Effective Length was selected based on the goodness-of-fit of the speed model.
- All of the unknown variables were calculated based on the best Effective Length.

The Purdue Research Team selected the proposed scheme for several of its key merits, including:

- It promised to return good estimations of the unknown variables based on real data.
- The speed model possesses the flexibility of estimating separating values for different vehicle classes and work zone categories.
- By using the speed model, the Purdue Research Team is able to verify the validity of both assumptions of driver behavior based on the model's performance.

From the literature and the speed model, we know very few studies have addressed effective length, but the Medina et al. study (*23*) suggested it should not go beyond 1.5 miles; and in this study, the effective length was investigated from 0–3 miles with 0.05 mile intervals, which is believed to be exhaustive.

Then, the variables needed to be transformed to facilitate the modeling. Under this new assumption, the model is different in several key aspects:

- Under the new assumption, the effectiveness of police enforcement at all locations will be the same (unless part of its effectiveness is outside the data collection region) regardless of the location of the enforcement unit.
- The length of the data collection segment also came into play under the new assumption. This is shown by the equation in the previous section.
- Overlapping of the effects of multiple enforcement units needed to be taken into consideration. According to the assumption, the a driver's perceived safe speed was the same, even if there were many closely spaced enforcement units. This assumption is consistent with the findings from Wasson et. al. (*34*), in which 12 enforcement units were used in a 12-mile freeway segment work zone.

In the original speed model, each enforcement unit in the work zone is represented by indicator variables, and the model coefficient is its effectiveness on average speed (ΔV). For the new model, since no differences were expected from different locations, one unified enforcement variable was used to replace all of the

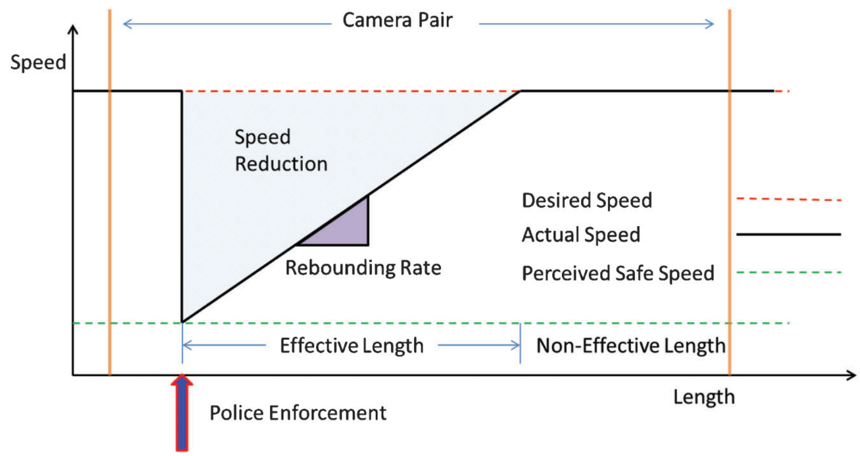

Figure 4.17 Speed Rebound Model: Scenario 1.

police vehicle variables (with the VMS variable kept separate in the model). This unified enforcement variable is the sum of the speed reduction effects (the area below the dashed red line and above the black line in the illustration) experienced for all of the enforcement units, averaged over the length of the data collection segment. From the equation in the previous section, the speed reduction caused by police enforcement is shown as:

$$\overline{\Delta V} = V_D - V_A = \frac{L_E * (Rr * L_E)/2}{Dist} = \frac{Rr * L_E^2}{2 * Dist}$$

While Dist is known from the data and L_E is assumed, the $L_E^2/2 * Dist$ part of the equation is known. Thus, the $L_E^2/(2 * Dist)$ was used as the transformed enforcement variable, and the Rr was estimated as the parameter coefficient from the speed model. This new enforcement variable is equivalent to the effectiveness of all the enforcement units, and thus is called the Enforcement Effectiveness Equivalent (EEE).

With the concept and transformation of the EEE variable explained, all of the possible scenarios regarding the effective length and overlapping of enforcement units was further illustrated, along with the corresponding calculation of the EEE.

Some new variables are explained here:

- **a:** the location of the police vehicle (the first one if there are multiple), measured from the location of the first camera, positive if it is downstream and negative if upstream.
- **b:** the location of the second police vehicle when there are more than one, measured from the location of the first camera, positive if it is downstream and negative if upstream.
- **Dist:** distance of the second camera from the first camera.

Scenario 1: One Enforcement Unit, All In (Figure 4.17). In this scenario, there was only one enforcement unit in the data collection segment, and the effectiveness of the unit was entirely captured by the camera pair. This is the most typical case and the calculation is the easiest, which the $\overline{\Delta V}$ is calculated as:

$$\overline{\Delta V} = \frac{L_E * (Rr * L_E)/2}{Dist} = \frac{Rr * L_E^2}{2 * Dist}$$

While the Rebounding Rate is to be estimated as the model parameter, the variable to be used for modeling, the EEE, is shown as:

$$EEE = \frac{L_E^2}{2 * Dist}$$

Scenario 2: One Enforcement Unit, Partially Before (Figure 4.18). In this scenario, there was one enforcement unit upstream of the data collection segment, thus the effectiveness was only partially captured. There were many cases where police vehicles were upstream of the data collection segment; and if their effectiveness reached the data collection segment, this was the scenario. The EEE is calculated as:

$$EEE = \frac{(a + L_E)^2}{2 * Dist}$$

Scenario 3: One Enforcement Unit, Partially Before & After (Figure 4.19). In this scenario, there was one enforcement unit upstream of the data collection segment, but the effectiveness extended beyond the end of the data collection segment. The EEE is calculated as:

$$EEE = \frac{(a + L_E)^2 - (a + L_E - Dist)^2}{2 * Dist}$$

Scenario 4: One Enforcement Unit, Partially After (Figure 4.20). In this scenario, there was one enforcement unit inside the data collection segment, but the effectiveness was only partially captured. The EEE is calculated as:

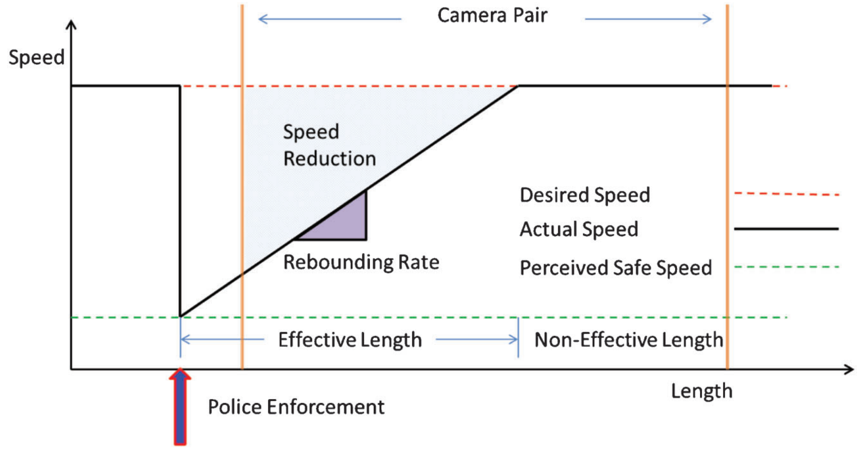

Figure 4.18 Speed Rebound Model: Scenario 2.

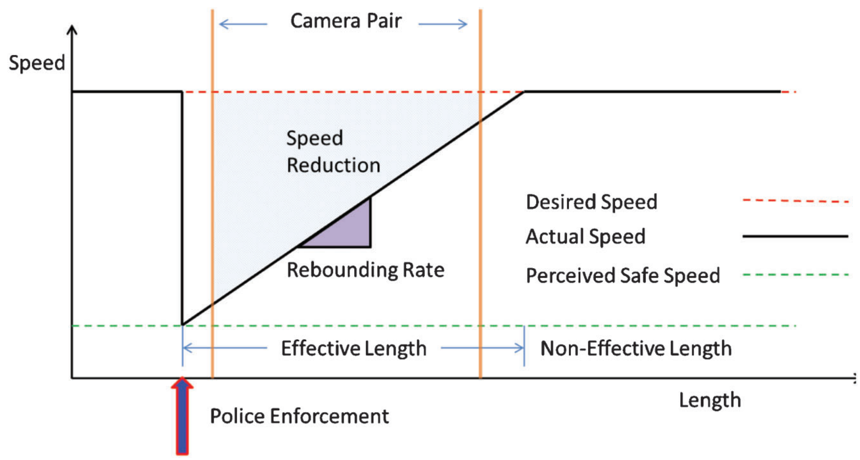

Figure 4.19 Speed Rebound Model: Scenario 3.

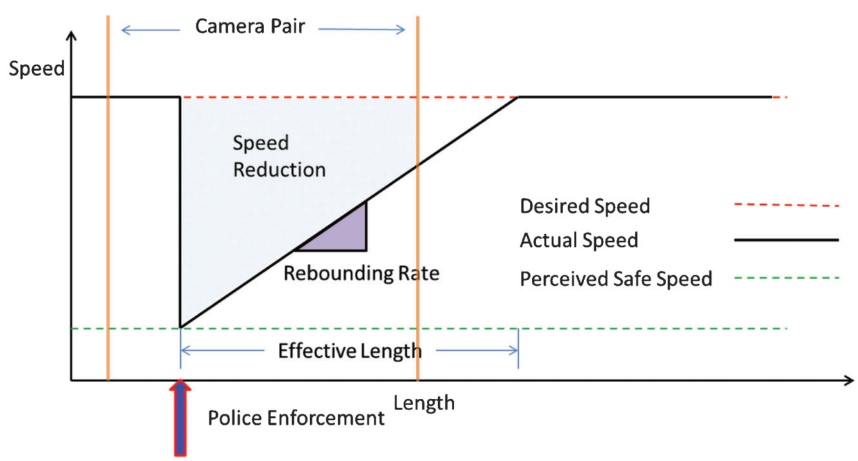

Figure 4.20 Speed Rebound Model: Scenario 4.

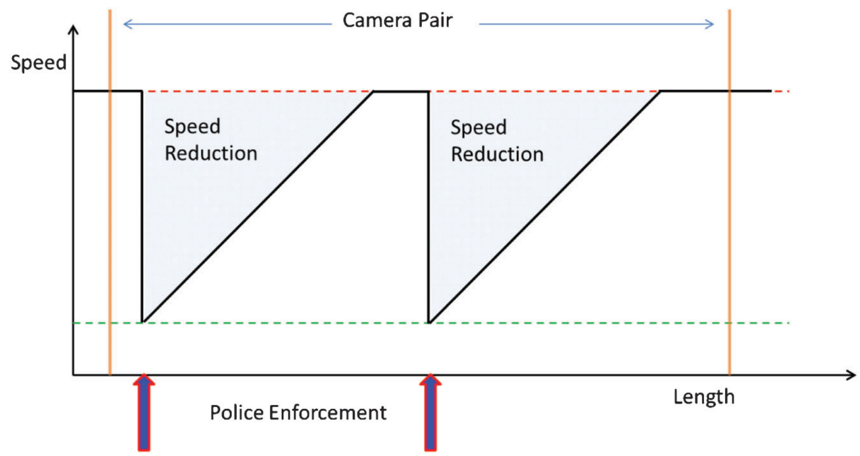

Figure 4.21 Speed Rebound Model: Scenario 5.

$$EEE = \frac{L_E{}^2 - (a + L_E - Dist)^2}{2 * Dist}$$

Scenario 5: Two Enforcement Units, All In, No Overlap (Figure 4.21). In this scenario, there were two enforcement units inside the data collection segment, the effectiveness of both were captured and there was no overlap. The calculation is sequential, calculating the effectiveness of the first unit, and then adding the effectiveness of the second unit to the first unit. The EEE is calculated as:

$$EEE = EEE_a + \frac{L_E{}^2}{2 * Dist}$$

Scenario 6: Two Enforcement Units, All In, With Overlap (Figure 4.22). In this scenario, there were two enforcement units inside the data collection segment, the effectiveness of both were captured, but there was overlap. The calculation first sums up the effectiveness of both, and then subtracts the overlap. The EEE is calculated as:

$$EEE = EEE_a + \frac{L_E{}^2 - (a + L_E - b)^2}{2 * Dist}$$

Scenario 7: Two Enforcement Units, Partially Before, With Overlap (Figure 4.23). In this scenario, there was one enforcement unit inside the data collection segment with another upstream, and there was overlap. The calculation is no different from the previous scenario since that is taken care of by EEE_a. The EEE is calculated as:

$$EEE = EEE_a + \frac{L_E{}^2 - (a + L_E - b)^2}{2 * Dist}$$

Scenario 8: Two Enforcement Units, Partially After, With Overlap (Figure 4.24). In this scenario, there were two enforcement units inside the data collection segment with the effectiveness of one extending after the segment, and there was overlap. The EEE is calculated as:

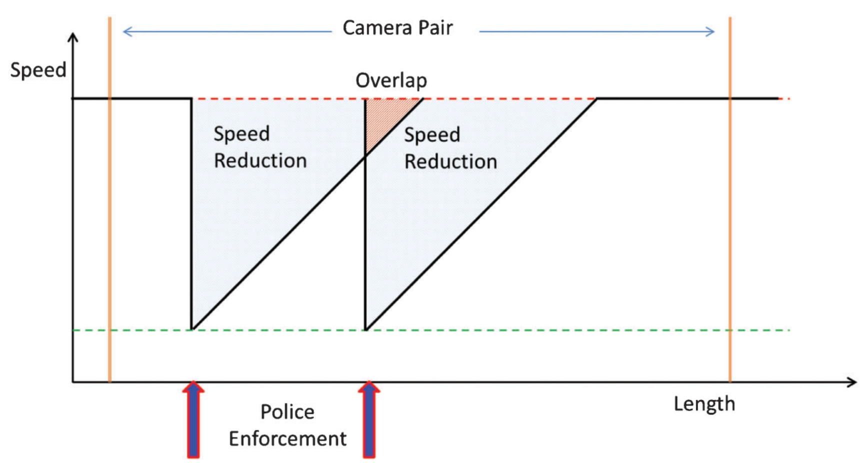

Figure 4.22 Speed Rebound Model: Scenario 6.

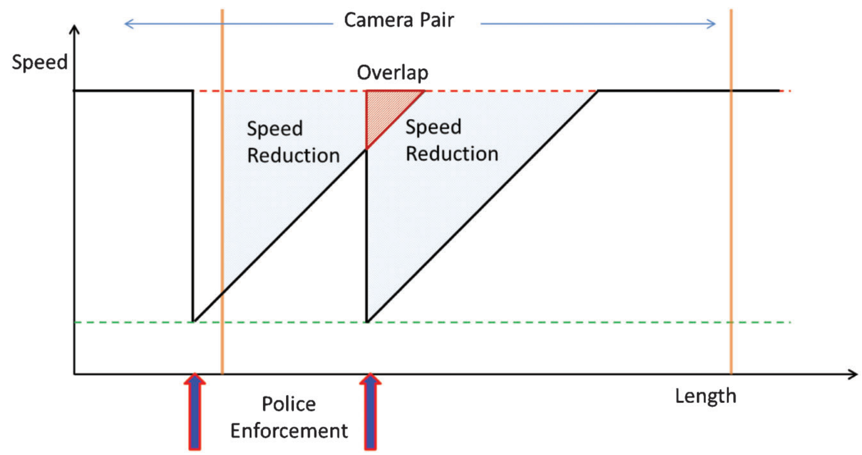

Figure 4.23 Speed Rebound Model: Scenario 7.

$$EEE = EEE_a + \frac{L_E{}^2 - (b + L_E - Dist)^2 - (a + L_E - b)^2}{2 * Dist}$$

Scenario 9: Two Enforcement Units, Both Partially Before, With Overlap (Figure 4.25). In this scenario, there were two enforcement units upstream of the data collection segment with the effectiveness of both extending into the segment, and there was overlap. The calculation is complicated; but there is no case like this in the dataset, for L_E of up to 3 miles.

Scenario 10: Two Enforcement Units, Both Partially After, With Overlap After (Figure 4.26). In this scenario, there were two enforcement units inside the data collection segment with the effectiveness of both extending after the segment, and thus also overlapping. The calculation should not double count the overlap part outside the data collection segment. The EEE is calculated as:

$$EEE = EEE_a + \frac{L_E^2 - (b + L_E - Dist)^2 - (a + L_E - b)^2 + (a + L_E - Dist)^2}{2 * Dist}$$

Scenario 11: Two Enforcement Units, Both Partially Before & After, With Overlap Before & After (Figure 4.27). In this scenario, there were two enforcement units upstream of the data collection segment with the effectiveness of both extending after the segment, and thus also overlapping. There is no case like this in the dataset, for L_E of up to 3 miles.

Also, for L_E of up to 3 miles, there were no cases with three enforcement units overlapping, which greatly simplified the data transformation process. In the end, a total of 60 EEE variables ranging from 0.05 mile to 3 miles, with 0.05 mile intervals created, which are stored in the dataset with their corresponding assumed L_E.

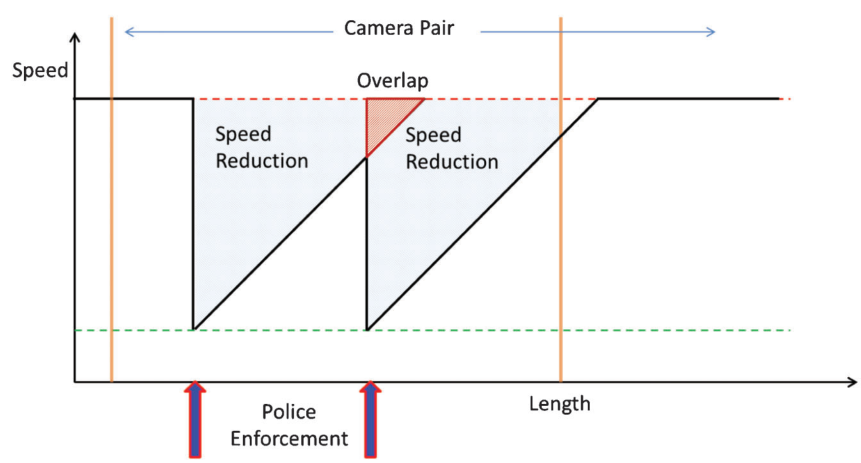

Figure 4.24 Speed Rebound Model: Scenario 8.

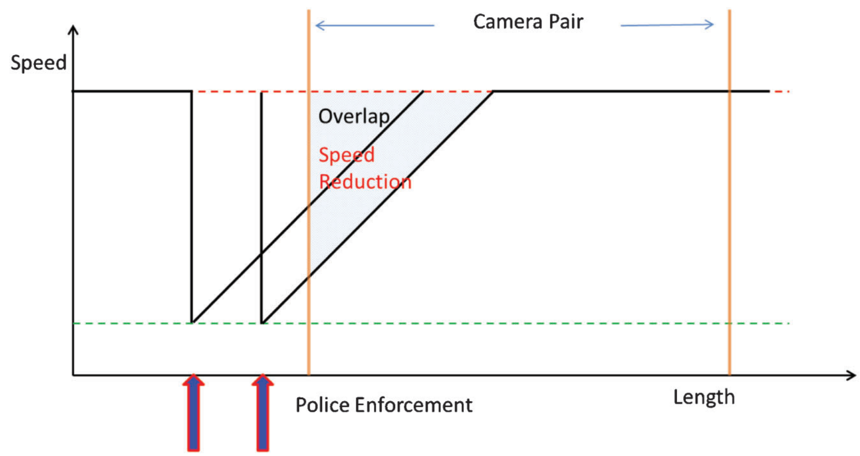

Figure 4.25 Speed Rebound Model: Scenario 9.

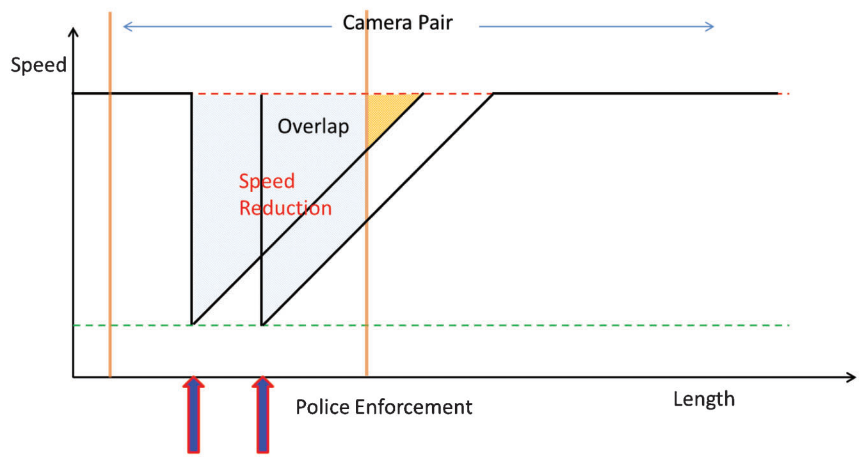

Figure 4.26 Speed Rebound Model: Scenario 10.

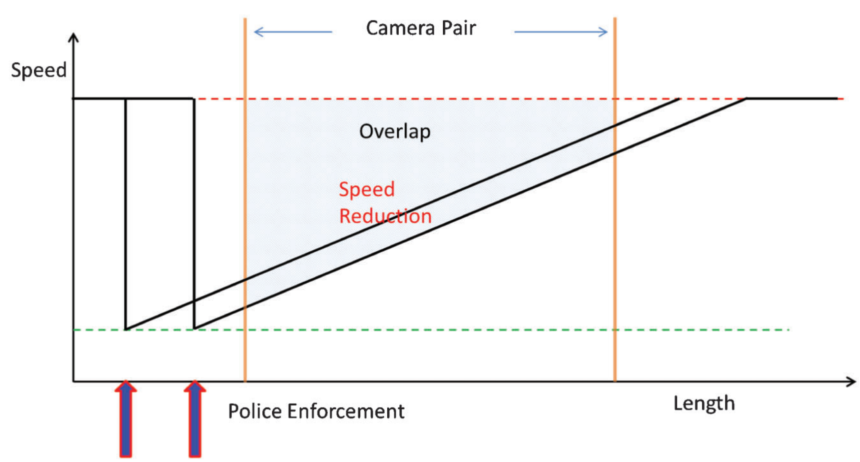

Figure 4.27 Speed Rebound Model: Scenario 11.

TABLE 4.11
Trials in Search for the Best Assumption of Effective Length

Effective Length (Mile)	-2 Log-Likelihood
0.50	49888.3
0.80	49886
0.90	49885.6
0.95	**49885.5**
1.00	49885.7
1.20	49888.4
1.50	49897.7
2.00	49914.6

4.4.3 Speed Model with EEE

The speed model possesses the flexibility of using a different effective distance and rebounding rate for both different work zone categorizations and vehicle classifications. In this practice, however, based on the assumption of driver behavior, the same effective length was used across work zone categories and vehicle types. But rebounding rates were allowed to be different for each work zone category and across vehicle classes where necessary. This way, the model could be fitted better, and one single value of effective length could be found, which is consistent with the Speed Rebound Model assumption.

The three level hierarchies and all of the covariances were kept from the random effect model. Also, all of the police vehicle variables were replaced with the EEE variables. Through trials, it was found that in Work Zone Category 1, trucks had significantly different rebounding rates from cars, while in other categories no significant differences were observed. By applying EEEs of different effective lengths to the model, the best effective length was identified based on the Log-Likelihood test, as shown in Table 4.11.

The -2 Log-Likelihood statistic is showing a convex shape, thus it is clear that the optimal value of the effective distance was 0.95 mile based on this dataset. The output of the speed model with a 0.95 mile effective distance is shown in Figure 4.28.

The parameter estimations revealed that the intercept, the estimates of the non-enforcement-related variables, and the VMS, were very similar to those from the original speed model.

The parameters for the EEE variables also appeared to be reasonable. All of the parameter estimations for the EEEs were negative, which reflects the speed reduction

```
The Mixed Procedure

Dimensions
Covariance Parameters              3
Columns in X                      19
Columns in Z                     156
Subjects                           1
Max Obs Per Subject             9428

Covariance Parameter Estimates
Cov Parm      Estimate
IDGroup         6.0837
IDSect          7.4231
Residual       11.0381

Fit Statistics
-2 Res Log Likelihood          49885.5
AIC (smaller is better)        49891.5
AICC (smaller is better)       49891.5
BIC (smaller is better)        49900.5

Solution for Fixed Effects
Effect                Estimate       STDEV      DF    t Value     Pr > |t|
WZ_cat1                57.4979      1.2715    9264      45.22       <.0001
WZ_cat1*VMS01          -3.7063      1.0140    9264      -3.66       0.0003
WZ_cat1*VMS45           0.7340      0.2640    9264       2.78       0.0054
WZ_cat1*hour0910       -0.9625      0.3421    9264      -2.81       0.0049
WZ_cat1*vol08plus      -1.0850      0.2768    9264      -3.92       <.0001
WZ_cat1*truck          -2.9272      0.1295    9264     -22.60       <.0001
WZ_cat2                45.5069      2.7708    9264      16.42       <.0001
truck*WZ_cat2          -2.1627      0.2661    9264      -8.13       <.0001
WZ_cat3                41.1629      2.9264    9264      14.07       <.0001
WZ_cat3*Semi           -1.0424      0.3214    9264      -3.24       0.0012
WZ_cat3*SU             -1.6764      0.4045    9264      -4.14       <.0001
WZ_cat4                44.4526      2.1680    9264      20.50       <.0001
WZ_cat4*VMSIn          -3.7309      1.7801    9264      -2.10       0.0361
WZ_cat1*car*LE095      -9.5908      0.5777    9264     -16.60       <.0001
WZ_cat1*SU*LE095       -7.9238      0.8034    9264      -9.86       <.0001
WZ_cat1*Semi*LE095     -8.4521      0.6690    9264     -12.63       <.0001
WZ_cat2*LE095          -2.1785      0.6407    9264      -3.40       0.0007
WZ_cat3*LE095          -4.3313      1.7828    9264      -2.43       0.0151
WZ_cat4*LE095          -6.5667     10.9251    9264      -0.60       0.5478
```

Figure 4.28 SAS output of the speed model with EEE.

TABLE 4.12
Summary of Enforcement Effects (Speed Rebound Model)

Work Zone Category	Vehicle Class	Rr	Vd	Delta V*	Vs
Cat-1	Car	9.591	57.498	-9.111	48.387
Cat-1	SU	7.924	54.571	-7.528	47.043
Cat-1	Semi	8.452	54.571	-8.029	46.541
Cat-2	Car	2.179	45.507	-2.070	43.437
Cat-2	SU	2.179	43.344	-2.070	41.275
Cat-2	Semi	2.179	43.344	-2.070	41.275
Cat-3	Car	4.331	41.163	-4.115	37.048
Cat-3	SU	4.331	40.121	-4.115	36.006
Cat-3	Semi	4.331	39.487	-4.115	35.372
Cat-4	All	6.567	44.453	-6.238	38.214

*Delta V is the difference between desired speed and perceived safe speed.

caused by the police enforcement. While interpreting the rebounding rates, however, the absolute values of the estimations were used. The unit for the rebounding rats is "mph/mile," which is the speed gained within a unit distance. Also, the absolute speed change was calculated by multiplying the rebounding rate and the effective distance. Comparison could not be made directly with the effectiveness from the original speed model since the speed reduction in the original speed model was measured in terms of average speed throughout the work zone, while here, it was the immediate speed reduction at the point of police enforcement. A summary of all the variables is shown in Table 4.12.

In Category 1, the rebounding rates were estimated for each vehicle class individually. The rebounding rate for cars was estimated to be 9.591 mph/mile. With an effective length of 0.95 miles, the absolute speed change when seeing police enforcement was 9.11 mph. The rebounding rates for single unit trucks and truck-trailers were relatively lower (but nonetheless higher than in other categories); with the same effective length, these translate to a lower speed reduction, but the Vs was still lower than that for cars, due to the lower Vd. These findings were consistent with the findings from the original speed model.

In Category 2, the rebounding rates were not significantly different among vehicle classes, thus only one parameter was estimated. The rebounding rate was estimated to be 2.179 mph/mile, which translates to an absolute speed change of 2.07 mph when seeing police enforcement. The smaller change in speed was the result of a relatively low Vd, which was barely higher than the legal speed limit.

In Category 3, there was also one rebounding rate estimated for all vehicle classes. With a rate of 4.331 mph/mile and an absolute speed change of 4.115 when seeing police enforcement, the effect was more significant due to a Vd that was significantly higher than the legal speed limit (35 mph).

As found in the original speed model, a five-mile-long, one-lane work zone, the Vd in Category 4 was lower than the legal speed limit to start with, in addition to the lack of overtaking opportunities and congestion problems, the Vs was found to be 38.214, which was much lower than the legal speed limit.

With all of the parameter estimations reasonable and consistent with the original speed model, the model fitting was compared to the original speed model. A Chi-Square Test (shown below in Table 4.13) was conducted with the Log-Likelihood from both models, and it was found that the fitting of the original speed model was better than the Speed Rebound Model at 99% significance level (critical Chi-Square value being 15.09).

With the conclusion that the Speed Rebound Model does not fit the data as well as the original speed model, the Purdue Research Team decided to use the assumptions for the original speed model and the effectiveness found in the original speed model. However, the most important achievement from the Speed Rebound Model was the identification of the effective length of police enforcement in work zones. Through modeling, the Purdue Research Team found that the effectiveness police enforcement on speed reduction in work zones totally dissipated within one mile or so. This finding will help the programming of police enforcement in work zones.

4.5 Enforcement Summary and Recommendation

Following is a summary of what was learned in this section of the study:

- Police patrol was not significant in terms of speed reduction.
- Stationary police enforcement showed significant effectiveness.

TABLE 4.13
Comparison of Original Speed Model and Speed Rebound Model

Model	Log-Likelihood	Number of Parameters
Original speed model	-24922.8	24
Speed Rebound Model	-24942.75	19
Difference	19.95	5

- VMS displaying enforcement messages also showed significant effectiveness.
- The effectiveness of stationary police enforcement and VMS both vary by location.
- The most effective location for stationary police enforcement is at the beginning of a work zone.
- The effective length for police enforcement is about one mile for each unit.
- The most cost-effective enforcement strategy for a single work zone is using one police vehicle at the beginning of a work zone and a VMS shortly upstream.

Thus, while programming for the work zone enforcement activities, the following recommendations were made:

- The first enforcement unit should be used for stationary police enforcement for all such work zone enforcement activities.
- Use VMS to display enforcement messages whenever available.
- Always put the first enforcement unit at the beginning of the work zone or the actual activity area.
- Additional enforcement units should be added only if the benefit-cost analysis shows additional units are more beneficial than spreading the resource to more work zones;
- Additional enforcement units should be performing active police enforcement, either visible or non-visible, to maintain the authority of enforcement activities.

The Optimizer is introduced in the next chapter, which will automatically perform all the calculations and recommend the most cost-effective enforcement strategies for all of the work zones, subject to all the constraints.

5. WORK ZONE ENFORCEMENT PROGRAMMING

The Police Enforcement Programming Tool uses integer optimization based on the results from the previous research components. The Optimizer aims to maximize the monetary benefit resulting from the police enforcement activities in highway work zones, subject to all constraints. Also, users have the flexibility to give priority to some work zones and to make sure certain work zones always get enforcement even though they might not be the most cost-effective choices.

The Optimizer requires inputs from the user and has the knowledge from the previous research components built in. Once all of the required inputs are in place, the Optimizer automatically calculates the benefit and costs. Then, once the user runs the optimization, the work zone and strategy combinations are chosen so that the benefits are maximized subject to all of the constraints. The following sections explain each component in detail.

5.1 Benefit

The benefit in this optimization problem is the monetary value of all crashes saved by the selected police enforcement strategies. The following components were used to calculate the benefits:

- Estimated crash frequency in work zones.
- Percentage of injury (including fatal) crashes.
- Percentage of crashes to be affected by police enforcement.
- Crash Modification Factors for various police enforcement strategies.
- Monetary cost for crashes at each injury level.

5.1.1 Estimated Number of Crashes in Work Zones

The first component is the result from the work zone crash prediction model. In Chapter 3, three models were described: one monthly observation historical model, one work zone level model, and one monthly observation prediction model. In the interim implementation tool, the work zone level model was incorporated and recommended to INDOT for implementation due to the fact that it does not require data processing and the calculation is relatively simple, thus making it easily implemented. For the final product of this project, however, the monthly observation prediction model was chosen since it provides the best model fitting. Although data processing is required, most of the steps are automated in the Optimizer and no extra burden is added on the users' side. Thus, the monthly observation prediction model is utilized to provide the baseline crash frequency in the Optimizer.

The crash frequency, according to the monthly observation work zone crash prediction model, is shown in the equation below:

$$\begin{aligned}A = {} & L^{0.8713} * (D * V)^{0.8324} * EXP[-4.5387 * Cat_1 - \\ & 5.1792 * Cat_2 - 5.5850 * Cat_3 - 5.2151 * Cat_4 \\ & + 1.4102 * U - 2.1989 * P - 0.0537 * LS - \\ & 0.0060 * RW + 0.1920 * SH + 0.2271 * SP + \\ & 0.1685 * NovDec + 0.1695 * MayJunJul + \\ & 0.6655 * LO + 0.7038 * HI]\end{aligned}$$

where:

A = expected number of crashes during the construction period,

L = work segment length (mi),

D = number of days,

V = average ADT during the construction period in 1000s veh/day,

Cat(1–4) = work zone categories,

U = fraction of the work zone length in an urban area,

P = fraction of the work zone length with a parking lane before the construction period,

LS = average width of the left shoulder (ft),

RW = average width of the right of way (ft),

SH = 1 if traffic lanes shift in the work zone, = 0, otherwise,

SP = 1 if traffic lanes were split in the work zone, = 0, otherwise,

NovDec = monthly indicator for November and December, = 0, otherwise,

MayJunJul = monthly indicator for May, June and July, = 0, otherwise,

LO = 1 if the low work intensity (construction cost <= $10000/day/mi), =0 otherwise.

HI = 1 if the high work intensity (construction cost > $35,000/day/mi), =0 otherwise.

This equation is built into the Optimizer. The user only needs to provide all of the required input data, and the crash frequency is automatically calculated.

5.1.2 Crash Injury Levels / Weekday / Daytime Percentages

The work zone crash frequency model provides the overall number of crashes in a work zone, but there neither is information about the likelihood of injury nor how many crashes will happen during the time when police enforcement would be present. Thus, further analysis is needed to provide such information.

The common practice is to estimate an injury severity model which estimates the likelihood of a crash being at a certain injury level, given a crash is to happen. However, a work zone injury severity model was not estimated due to the sample size issue. Thus, without an injury severity model, the percentage of injury (including all injury levels and fatal) crashes for both work zones and the entire state of Indiana was calculated and compared. If these two percentages are not significantly different from one another, we can conclude that the injury likelihood in work zones generally follows the pattern of the entire road network, and the percentage from the entire state of Indiana would be used for a much larger sample size and eventually much better statistical properties. Otherwise, when these two percentages are significantly different, certain inferences need to be made and the percentage for the work zones will be used. This is done for each type of roads (urban and rural, freeway and non-freeway).

The same analysis was done for the day/night and weekday/weekend distribution of crashes. The percentage was calculated for all of the work zones of different road classification and then verified against the entire state of Indiana.

The number of PDO/Injury crashes, weekday/weekend, day/night crashes at four different road classes, for all the work zones in the sample and the entire state of Indiana are shown in Table 5.1, followed by the corresponding percentages in Table 5.2. The columns with highlighted background are the type of crashes that will be affected by the police enforcement.

To facilitate statistical tests, the following three set of percentages were calculated: day versus night, weekday versus weekend, and Injury versus PDO. The percentages are shown in Table 5.3. Assuming each crash is a Bernoulli trial, t-tests were carried out to see whether the percentages for the work zone sample and the entire state of Indiana were statistically different. From the results in Table 5.4, the only differences were found for the day versus night percentage, in urban freeway and rural non-freeways, with all others not significantly different. The higher share of daytime crashes in work zones might suggest that the construction activities are related to more crashes as most construction work is conducted during the daytime.

Thus, for calculation of the crashes affected by police enforcement, the work zone daytime percentage for urban freeway and rural non-freeways was used, due to the significant differences. For all other percentages, the percentages for the entire state of Indiana were used due to their much larger sample size and better confidence. The final percentages are shown in Table 5.5.

After this step, the numbers of PDO and Injury crashes that will be affected by the police enforcement are calculated as:

$$C_{PDO} = C_{Tot} * P_{PDO} * P_{Weekday} * P_{Day}$$

$$C_{Injury} = C_{Tot} * P_{Injury} * P_{Weekday} * P_{Day}$$

Where C is the frequency of crashes in a certain injury category, and P is the percentage for a certain category out of the total crashes, as shown in Table 5.5.

TABLE 5.1
Crash Frequency in Work Zones and State of Indiana

Crash Counts		All Work Zone (72 Sample Size)				All State of Indiana			
Road Classification	**Injury Level**	**Weekend—Day**	**Weekend—Night**	**Weekday—Day**	**Weekday—Night**	**Weekend—Day**	**Weekend—Night**	**Weekday—Day**	**Weekday—Night**
Urban freeway	Injury	13	13	**47**	26	465	542	**1753**	1332
	PDO	68	42	**278**	176	2003	2048	**8558**	6568
Urban non-freeway	Injury	16	13	**55**	21	11418	9524	**41196**	22979
	PDO	63	44	**223**	100	42843	30252	**175602**	84129
Rural freeway	Injury	2	5	**14**	12	355	348	**757**	810
	PDO	30	31	**65**	59	1455	1930	**4048**	4759
Rural non-freeway	Injury	15	6	**38**	23	4566	4373	**12593**	9579
	PDO	33	32	**115**	79	10886	12630	**35554**	35235

TABLE 5.2
Distribution of Crashes in Work Zones and State of Indiana

Crash Percentages		All Work Zone (72 Sample Size)				All State of Indiana			
Road Classification	**Injury Level**	**Weekend—Day**	**Weekend—Night**	**Weekday—Day**	**Weekday—Night**	**Weekend—Day**	**Weekend—Night**	**Weekday—Day**	**Weekday—Night**
Urban freeway	Injury	1.96%	1.96%	**7.09%**	3.92%	2.00%	2.33%	**7.53%**	5.72%
	PDO	10.26%	6.33%	**41.93%**	26.55%	8.61%	8.80%	**36.78%**	28.23%
Urban non-freeway	Injury	2.99%	2.43%	**10.28%**	3.93%	2.73%	2.28%	**9.86%**	5.50%
	PDO	11.78%	8.22%	**41.68%**	18.69%	10.25%	7.24%	**42.02%**	20.13%
Rural freeway	Injury	0.92%	2.29%	**6.42%**	5.50%	2.45%	2.41%	**5.23%**	5.60%
	PDO	13.76%	14.22%	**29.82%**	27.06%	10.06%	13.35%	**27.99%**	32.91%
Rural non-freeway	Injury	4.40%	1.76%	**11.14%**	6.74%	3.64%	3.49%	**10.04%**	7.64%
	PDO	9.68%	9.38%	**33.72%**	23.17%	8.68%	10.07%	**28.35%**	28.09%

TABLE 5.3
Crash Percentages in Work Zones and State of Indiana

Percentages		All Work Zone (72 Sample Size)			All State of Indiana		
Road Classification	**Variable**	**Day (vs Night)**	**Weekday (vs Weekend)**	**Injury (vs PDO)**	**Day (vs Night)**	**Weekday (vs Weekend)**	**Injury (vs PDO)**
Urban freeway	Mean	0.6124	0.7949	0.1493	0.5492	0.7826	0.1759
	Variance	0.2374	0.1631	0.1270	0.2476	0.1701	0.1449
Urban non-freeway	Mean	0.6673	0.7458	0.1963	0.6486	0.7750	0.2037
	Variance	0.2220	0.1896	0.1577	0.2279	0.1744	0.1622
Rural freeway	Mean	0.5092	0.6881	0.1514	0.4574	0.7173	0.1570
	Variance	0.2499	0.2146	0.1285	0.2482	0.2028	0.1323
Rural non-freeway	Mean	0.5894	0.7478	0.2405	0.5071	0.7412	0.2481
	Variance	0.2420	0.1886	0.1826	0.2499	0.1918	0.1865

TABLE 5.4
Statistical Comparison of Crash Percentages

Road Classification	Variable	Day (vs Night)	Weekday (vs end)	Injury (vs PDO)
Urban freeway	t-test	**3.2258**	0.1056	−0.2488
	95% Significance	**Yes**	No	No
Urban non-freeway	t-test	0.9071	−0.2796	−0.0662
	95% Significance	No	No	No
Rural freeway	t-test	1.5228	−0.0916	−0.0341
	95% Significance	No	No	No
Rural non-freeway	t-test	**3.0373**	0.0581	−0.0430
	95% Significance	**Yes**	No	No

TABLE 5.5
Final Crash Percentages Used for Enforcement Programming

Road Classification	Weekday	Daytime	Injury	PDO
Urban freeway	0.7826	0.6124	0.1759	0.8241
Urban non-freeway	0.7750	0.6486	0.2037	0.7963
Rural freeway	0.7173	0.4574	0.1570	0.8430
Rural non-freeway	0.7412	0.5894	0.2481	0.7519

This step is also automated in the Optimizer.

5.1.3 Crash Modification Factors

Crash Modification Factors (CMF) or Crash Reduction Factors (CRF) are ubiquitously used to evaluate the effectiveness of road safety improvement techniques. In the second major research component of this study, the effectiveness of police enforcement was evaluated in terms of speed reduction, which needs to be converted to CMFs for the calculation of benefits.

The Power Model by Elvik (*1*) provides a great link between speed reduction and crash reduction. The updated Power Model provided separate sets of exponents for city/residential roads and rural/high speed roads. Although the Power Model did not specifically consider work zones, it is believed that the Power Model is nonetheless the best available source to convert speed reduction in work zones into crash reduction.

The formulation of the Power Model is very simple, as shown in the equation below:

$$\frac{\text{Crashes After}}{\text{Crashes Before}} = \left(\frac{\text{Speed After}}{\text{Speed Before}}\right)^{\text{Exponent}}$$

It is assumed in the Power Model that the percent change in speed will affect the percent change in crashes exponentially. The exponents differ by injury categories and in the updated version of Power Model, by road types also. For our application of highway work zone enforcement, the exponent for rural/high speed roads was used. The Power Model provides the exponents for four different injury levels: PDO, slight injury, serious injury, and fatality, along with for all levels of injury status (including fatal and non-injury). The numbers of crashes were calculated for only two injury levels, PDO and all injury; thus, the exponents for PDO and all injury were taken from the Power Model. For PDO crashes, the mean estimate of the exponent is 1.5 and for injury crashes 1.6. The speed reduction and the calculated CMFs are shown in Table 5.6 and Table 5.7. Notice that, for Work Zone Categories 2 and 3, the addition of the third police vehicle (for one direction) did not bring additional speed reduction so the CMFs for the strategies with two and three police vehicles (each direction) are the same. For Work Zone Category 4, the only significant enforcement strategies were the police vehicle at the beginning of work zone and the VMS (for one direction), with no further effectiveness found for additional police vehicles. This was also reflected in the CMFs.

In the input files, the truck percentage is available so the CMF for cars and truck-trailers will be combined for each injury category.

The calculation of CMF will be done automatically in the Optimizer as well.

5.1.4 Crash Costs

The final component needed for calculating the benefit of police enforcement is the average crash cost for each level of crashes. The average crash cost between 2008 and 2010 was calculated in the 2011 Five-Percent Report (*48*), which is shown in Table 5.8.

With the average crash cost, the total benefit of the police enforcement could be calculated as:

TABLE 5.6
Speed Reduction for Each Work Zone Category & Enforcement Strategy

Work Zone Category	Vehicle Type	Speed Without Enforce-ment	Speed Reduction						Percent Original Speed					
			No VMS			With VMS			No VMS			With VMS		
			EFC-1	EFC-2	EFC-3	EFC-1	EFC-2	EFC-3	EFC-1	EFC-2	EFC-3	EFC-1	EFC-2	EFC-3
WZ-Category-1	Car	57.21	3.28	5.75	8.22	6.89	9.36	11.83	94.27%	89.95%	85.63%	87.96%	83.64%	79.32%
	Semi	54.54	2.45	6.06	9.67	5.13	8.74	12.35	95.51%	88.89%	82.27%	90.59%	83.98%	77.36%
WZ-Category-2	Car	45.37	0.73	1.46	1.46	3.23	3.96	3.96	98.39%	96.78%	96.78%	92.88%	91.27%	91.27%
	Semi	43.19	0.73	1.46	1.46	3.23	3.96	3.96	98.31%	96.62%	96.62%	92.52%	90.83%	90.83%
WZ-Category-3	Car	40.97	2.04	4.08	4.08	4.54	6.58	6.58	95.02%	90.04%	90.04%	88.92%	83.94%	83.94%
	Semi	39.36	2.04	2.34	2.34	4.54	4.84	4.84	94.82%	94.05%	94.05%	88.47%	87.70%	87.70%
WZ-Category-4	Car	44.83	2.20	2.20	2.20	5.77	5.77	5.77	95.09%	95.09%	95.09%	87.13%	87.13%	87.13%
	Semi	44.83	2.20	2.20	2.20	5.77	5.77	5.77	95.09%	95.09%	95.09%	87.13%	87.13%	87.13%

TABLE 5.7
Crash Modification Factors (CMF) for Each Work Zone Category & Enforcement Strategy

Work Zone Category	Vehicle Type	Injury Crash Modification Factor						PDO Crash Modification Factor					
		No VMS			With VMS			No VMS			With VMS		
		EFC-1	EFC-2	EFC-3	EFC-1	EFC-2	EFC-3	EFC-1	EFC-2	EFC-3	EFC-1	EFC-2	EFC-3
WZ-Category-1	Car	0.9099	0.8441	0.7802	0.8144	0.7514	0.6903	0.9152	0.8531	0.7924	0.8249	0.7649	0.7065
	Semi	0.9291	0.8282	0.7318	0.8538	0.7562	0.6631	0.9334	0.8381	0.7462	0.8623	0.7695	0.6804
WZ-Category-2	Car	0.9744	0.9490	0.9490	0.8885	0.8640	0.8640	0.9760	0.9521	0.9521	0.8951	0.8720	0.8720
	Semi	0.9731	0.9465	0.9465	0.8831	0.8574	0.8574	0.9748	0.9497	0.9497	0.8899	0.8657	0.8657
WZ-Category-3	Car	0.9215	0.8455	0.8455	0.8287	0.7557	0.7557	0.9262	0.8544	0.8544	0.8385	0.7690	0.7690
	Semi	0.9184	0.9066	0.9066	0.8219	0.8106	0.8106	0.9233	0.9122	0.9122	0.8321	0.8213	0.8213
WZ-Category-4	Car	0.9226	0.9226	0.9226	0.8022	0.8022	0.8022	0.9273	0.9273	0.9273	0.8133	0.8133	0.8133
	Semi	0.9226	0.9226	0.9226	0.8022	0.8022	0.8022	0.9273	0.9273	0.9273	0.8133	0.8133	0.8133

$$\text{Benefit}_k = C_{PDO} * (1 - CMF_{PDOk}) * \text{Cost}_{PDO} + C_{Injury} * \left(1 - CMF_{Injuryk}\right) * \text{Cost}_{Injury}$$

Where the k is the corresponding police enforcement strategy.

In the Optimizer, once the user provided all the inputs, all the calculations towards the benefit will be automatically done in Excel.

5.2 Cost

The calculation of cost is much more straightforward compared to the benefit. There are three components of cost related to work zone enforcement: the rates paid to participating ISP officers; the operating cost for using the VMS; and the transportation cost for moving the VMS.

The police officers participating in work zone enforcement details are paid at a fixed rate. Other than the hours they are actually enforcing in the work zone, they are paid an additional hour for going to and coming back from the work zone. Thus, for the assumed 10 hours of enforcement per weekday, the cost will be 11 times the hourly rate. Also, since the numbers of weekdays vary by month, in the Optimizer, the number of actual enforcement days is calculated as the days in that month multiplied by 5/7. Thus, decimal points could (and almost always will) be present.

The operating cost for VMS is calculated in the same way as the rate for ISP police officers, with the only difference being that a daily rate is assumed for VMS compared to the hourly rate for ISP officers. It is unknown to the Purdue Research Team what the cost would be for operating the VMS, thus the user will input that cost.

TABLE 5.8
Average Crash Cost (Injury/PDO) in State of Indiana

Injury Level	Injury	PDO
Average crash cost for entire Indiana	65,708.36	6,507.70

Also, transporting the VMS will generate a small amount of cost. This cost is also considered in the Optimizer. However, the transportation cost for the VMS is considered to be a fixed amount cost opposed to calculating the rate by distance and location, which greatly complicates the issue. Like the VMS operating cost, the user will input this cost.

The calculations for the cost are relatively easy, which are also automated.

5.3 Constraints and Objective Function

Many constraints will affect police enforcement in work zones. These constraints are grouped into two major categories: constraints that prevents certain enforcement strategies to be implemented and constraints that come into effect during the optimization process.

5.3.1 Constraints Affecting Available Strategies

The constraints that prevent implementation of certain enforcement strategies are mainly related to work zone characteristics. During the field data collection efforts, the Purdue Research Team identified several factors that prevent certain desirable police enforcement strategies to be implemented:

- Categorization of work zones (prevents using more police vehicles to be effective, reflected in CMF).
- Length of work zone (prevents more police vehicles being used).
- Presence of concrete barriers (or other obstacles that prevents police vehicles from being stationed inside work zones).

Categorization. The variable, categorization of the work zone, will be automatically generated from the known variables; and the Optimizer will calculate the CMF based on the categorization. For the strategies that bring no additional benefit, the CMF will simply remain the same even though more police vehicles were used. Strategies with the same benefit but a higher cost will never be selected by the Optimizer.

Length. The length of the work zone is also a required input, thus the Optimizer will automatically evaluate each work zone and apply the empirically assigned maximum number of police vehicles allowed. Based on the findings from the Speed Rebound Model, the effective distance of enforcement is roughly one mile so the rules regarding the maximum number of police vehicles allowed are shown in Table 5.9.

According to Table 5.9, if a work zone is shorter than 1.6 miles in length, only one police vehicle on each direction will be allowed. If the work zone is between 1.6 and 3 miles in length, a maximum of two police vehicles per direction will be allowed. When the work zone is longer than 3 miles, a maximum of three police vehicles per direction will be allowed. The realization of this limit is taken care of by the benefit. When a strategy is using more than the maximum allowed number of police enforcement units, no additional benefit will be added beyond the maximum allowed.

Barriers and obstacles. The presence of concrete barriers or other obstacles that prevent police vehicles from safely and conveniently being stationed inside the work zone is also an important and required input. However, such information would not be readily available from any dataset or construction documents, but rather require field observation.

Thus, in the Optimizer, the default assumption is that police vehicles could be safety stationed inside the work zones. The user only needs to change that variable when field observation suggests there is no safe and convenient location for police vehicles inside the work zone. The realization of this limit is also taken care of by the benefit, as for the length.

More constraints of this type could be present, but the authors have only identified the above three during the field data collection activities. As long as corresponding input information was provided to the Optimizer, it will automatically apply all these restrictions.

5.3.2 Constraints Affecting Optimization

Other types of constraints do not eliminate available enforcement strategies, but will come into effect during the optimization process. The following are the constraints that are currently included in the optimizer:

- Available budget
- Available number of VMS (INDOT district)
- Available number of police units (ISP district)

TABLE 5.9
Work Zone Length and Maximum Number of Police Enforcement Units

Maximum Number of Police Vehicles Allowed (Each Direction)	Work Zone Length (Miles)
1	0–1.6
2	1.6–3
3	3–Infinite

- Total strategy constraint
- User selected Enforcement

Budget constraint. The budget constraint is very straightforward. Whether the user is planning the enforcement activities for the next fiscal year or is fine tuning the programming for the next month, the total cost of the enforcement activities should always stays under the budget.

However, not all parts of the related costs are charged to the ISP enforcement budget. Any cost related to the use of VMS is supposed to be charged from a separate pool. The Purdue Research Team assumed that, as long as INDOT indicates there is VMS available for enforcement, the cost of such VMS operations is also covered. To get a better picture of the benefit and cost situation, the VMS cost is accounted for by the objective function, which will be introduced later.

VMS availability. Availability of VMS is an important constraint, and the information should be known well ahead of time and be relatively stable. During the enforcement experiment, the Purdue Research Team experienced the lack of available VMS while planning for enforcement activities. The VMS are available from INDOT sub-districts.

ISP officer availability. Availability of ISP police units is without a doubt one of the most important constraints. However, unfortunately, due to the nature of the work zone enforcement activity, and the duties of ISP officers, their availability cannot be guaranteed and is always subject to changes, even without advanced notice. During the enforcement experiment, the Purdue Research Team experienced cases that ISP officers had to cancel the enforcement detail, even though such assignments were voluntarily signed up just one week in advance. Thus, great uncertainty will be expected for the availability of ISP officers. The ISP officers can only sign up to their corresponding jurisdiction, as shown in Figure 5.1.

Total strategy. This constraint is rather straightforward. We all understand very well that, for a given work zone, it can have only one enforcement strategy for a given month, and the Optimizer needs to know this. Thus, this constraint simply serves this purpose.

User enforcement decision. This constraint gives the user the flexibility of overriding the Optimizer and manually selecting work zones for enforcement (or no enforcement). In the input section, one column will ask the user whether the user wants the work zone to: 1) let the Optimizer decide; 2) get enforcement regardless of the Optimizer (for selected months), or 3) do not get enforcement regardless of the Optimizer (for selected months). When "Yes" is selected in the user enforcement decision and a specific time period

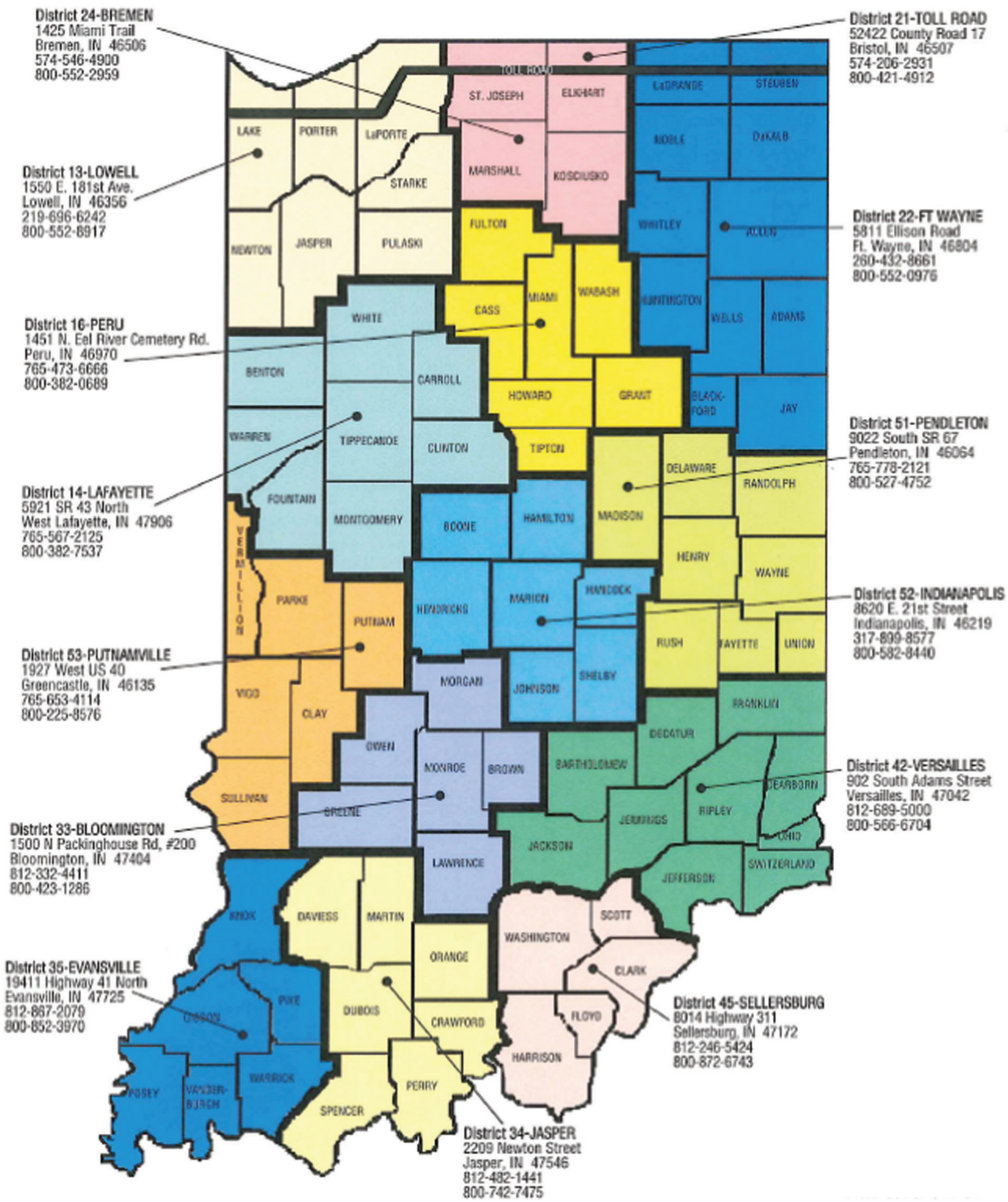

Figure 5.1 ISP district map.

is given, this work zone will always get enforcement for that period. However, the Optimizer will decide which strategy these work zones will get, based on the benefit and cost analysis and subject to all constraints.

This user enforcement decision is also done on a monthly basis. This will be introduced in more detail in the input section.

5.3.3 Objective Function

The objective function in this optimization problem is the safety benefit as a result of the enforcement activities in the highway work zones, minus the cost of operating VMS used for such enforcement activities. The calculation of the safety benefit was introduced in detail in the previous section. The cost for VMS is included in the objective function simply because this part of the cost comes from a different source of funding, thus it should not be included in the police enforcement cost. But to provide a better idea of what really is the benefit (excluding the VMS cost), the benefit and VMS cost were presented separately in the Optimizer and in the "RESULT" window.

The objective function is also automatically calculated, requires no user input.

5.4 Optimizer

Monthly observations were used for the work zone crash prediction model, so it is able to calculate the benefit of enforcement for each month. Thus, to be as accurate as possible, the Optimizer is also structured on a monthly basis. Not only does this monthly-based Optimizer provide more accurate estimation of benefit (no difference for the cost though), it provides the flexibility to rerun the optimization each month, as the enforcement activity goes on and as the constraints change.

The calculations of the Optimizer were introduced in the previous sections, here in this section, the user inputs, the logic of the Optimizer itself, along with the organization of the results will be introduced in detail.

5.4.1 Optimization Formulation

With the calculations and constraints introduced before, the optimization process in the Optimizer is introduced in this section. The equations below show the optimization formulation:

$$\max_{\{X\}} \sum_{\substack{i\in\{I\} \\ k\in\{K_i\} \\ tmin_i \le t \le tmax_i}} (X_{ikt}B_{ikt} - CV_{ikt})$$

st:

One budget constraint

$$\sum_{\substack{i\in\{I\} \\ k\in\{K_i\} \\ tmin_i \le t \le tmax_i}} X_{ikt}C_{ikt} \le \text{Budget}$$

One constraint for each area j and time interval t

$$\sum_{\substack{i\in\{I_j\} \\ k\in\{K_i\}}} X_{ikt}PU_{ikt} \le \text{Max } PU_{jt}$$

One constraint for each area j and time interval t

$$\sum_{\substack{i\in\{I_j\} \\ k\in\{K_i\}}} X_{ikt}VMS_{ikt} \le \text{Max } VMS_{jt}$$

One constraint per each work zone i and time interval t

$$\sum_{k\in\{K_i\}} X_{ikt} \le 1$$

One constraint for user selected enforcement in work zone i and time interval t

$$\sum_{k\in\{K_i\}} X_{ikt} = 1(\text{when "Yes"}) \text{ or } 0(\text{when "No"})$$

Where:

i = work zone index,

k = enforcement strategy index,

t = time interval index,

j = area index,

{I} = set of work zone indices,

{Ij} = subset of work zone indices for area j,

{Ki} = set of indices of enforcement strategies applicable to work zone i,

tmini = index of the first time interval with work zone i period,

tmaxi = index of the last time interval with work zone i period,

X_{ikt} = 1 if strategy k is applied in work zone i in time interval, = 0 otherwise,

{X} = complete set of decision variables,

B_{ikt} = benefit of deploying police enforcement strategy k in work zone i and in time interval,

C_{ikt} = cost paid to ISP officers for deploying strategy k in work zone i and in time interval,

CV_{ikt} = cost for VMS for deploying strategy k in work zone i and in time interval,

PU_{ik} = number of police units deployed by police enforcement strategy k in work zone i,

VMS_{ik} = number of VMS units deployed by police enforcement strategy k in work zone i,

Max PU_{jt} = number of police units available in area j during time interval t,

Max VMS_{jt} = number of VMS units available in area j during time interval t.

As the Optimizer could be run for any time interval, the user can run it for the entire fiscal year, the rest of the year, or even for a single month, by simply adjusting the time interval t. Also, constraints can be updated any time, and the Optimizer can be rerun to get the most up-to-date strategies.

Also, the dimension of this optimization problem is too large for the Excel® built-in Solver®. The Purdue Research Team sought help from external programs. The OpenSolver® (*2*) is an Excel VBA based program developed by Andrew Mason and students at the Engineering Science department, University of Auckland, NZ. After testing, the OpenSolver is totally capable of our programming needs, and is perfectly compatible with Microsoft Excel, as no issues of any kind has been encountered during the developing and testing phases. Thus, the OpenSolver will be used to solve the optimization problem in our work zone enforcement programming tool.

5.4.2 User Inputs

There is a large amount of calculations in the Optimizer, thus a large amount of inputs is needed. Luckily, most of the inputs are either readily available within INDOT, or already incorporated into the Optimizer by the Purdue Research Team. This section will describe the sources of input data and what the users have to do to run the Optimizer.

Five major categories of input data are needed, namely, pre-construction roadway characteristics, work zone features, knowledge of benefit and cost, constraints information, and user preferences. They will be introduced in the following sections.

Roadway Characteristics. Pre-construction roadway characteristics are needed mostly for predicting crash frequency and also for categorization of roadway and work zone types. In the work zone crash modeling, the following variables are used:

- Fraction of length in the urban area
- Fraction of length with parking lane
- Average width of the left shoulder
- Average width of the right of way
- Average Annual Daily Traffic

Also, two variables not directly used in the model, but is used for categorization of road segment type or work zone type, they are:

- Functional classification of the road
- Presence of system interchange

All this information should be readily available, or only require minimum data processing. This part of the information will be entered to "INPUT2" window, which includes all the information regarding individual work zones.

Work Zone Features. It is obvious that he work zone features will be essential for the Optimizer. These features were used both in the work zone crash modeling and in the estimation of the CMFs. The work zone features used for the calculations are:

- Work Zone Identification Information
- Jurisdictional Information (District, County)
- Starting and ending dates
- Work zone length
- Total award
- Presence of lane shifts
- Presence of lane splits
- Presence of concrete barriers or other obstacles (needs detailed field observation)
- Number of lanes opens to traffic

All of this information should be available from the Contract Information Book or other contract or construction documents. The only information which requires some extra effort is the presence of concrete barriers or other obstacles, since closer look of the drawing or field observation need to be taken to evaluate whether police vehicles could be safely and conveniently stationed inside the work zone.

This part of the information will also be entered to "INPUT2" window, which includes all the information regarding work zones.

Knowledge of Benefit & Cost. To calculate the benefit of police enforcement, two models (the work zone crash model and the speed model) and a lot of processing and adjustments are needed. All of these steps were included by the Purdue Research Team, as the Optimizer contains all of this information and all of the calculations are automated. Thus, no input or user action is needed for this part.

For the cost part however, user inputs are needed. The hourly rate for ISP officers and the daily cost and transportation cost for VMS is all that is needed for the calculation of cost. This part of the information will be entered to "INPUT1" window, which includes all the general information.

Constraint Information. Constraints were discussed in detail in an earlier section so they will not be repeated here. This part of the information will also be entered to "INPUT1", which includes all of the general information.

User Enforcement Decision. Due to various reasons that cannot be captured by the models and the benefit/ cost analysis, the user may want to select certain work zones for enforcement (or no enforcement) regardless of the results given by the benefit cost analysis. In this optimizer, such flexibility was incorporated.

In the "INPUT2" window, alongside the work zone features input, there is a column "User Enforcement Decision". The user will be selecting from a dropdown list, and the options are: 1) Blank, 2) Yes, and 3) No. The default setting is "Blank", which will leave all the decisions to the Optimizer.

If the user selected "Yes," the optimizer will modify the constraint from:

$$\sum_{k \in \{K_i\}} X_{ikt} \leq 1$$

To:

$$\sum_{k \in \{K_i\}} X_{ikt} = 1$$

Also, as can be seen from the constraint, the time period is flexible. Once the user selected "Yes" in the "User Selected Enforcement", the user can further specify the starting and ending month of such selected enforcement. For example, the user might want to make sure two work zones receive enforcement for the first month of the construction period (starting in April), select "Yes" in the "User Enforcement Decision", and put "4" in both the starting and ending month.

Also, from the constraint it is known that, the enforcement strategy is yet to be decided. As previously described, the Optimizer will find the most cost-effective enforcement strategy for such work zones, subject to all constraints.

If the user selected "No", the optimizer will modify the constraint from:

$$\sum_{k \in \{K_i\}} X_{ikt} \le 1$$

To:

$$\sum_{k \in \{K_i\}} X_{ikt} = 0$$

Since the decision variables are all binary, this is to force all the decision variables for this work zone to be 0. If such decision is applied for the entire fiscal year, the effect is equivalent to simply deleting this work zone from the list. But the user can still see the benefit and cost information for this work zone.

5.5 Results Presentation

The results from the optimization include two parts: one page presents all of the selected enforcement strategies, along with the benefit/cost information for the selected strategies; and in the more detailed results, the user can find all information regarding the benefit, cost, predicted number of crashes, CMF, etc.

5.5.1 Selected Strategies

In the Optimizer, the enforcement strategies are optimized on a monthly basis. Thus, in the final results presentation, a matrix of these decision variables is presented. Also, the benefit and cost information are presented for the entire fiscal year of each work zone.

In the "RESULT 1" window, for each work zone, first some basic information of each work zone is presented for identification purpose. Contract ID, District, County, and on road were presented.

Then, the selected enforcement strategy for each month is presented in a matrix. If a given work zone is not enforced for a given month, the cell will be simply left blank. If it is enforced for a given month, the type of strategy used will be presented in the corresponding cell. When enforced, the total benefit and total cost for the entire fiscal year will be summed, and the benefit/cost ratio calculated, for each work zone.

5.5.2 Benefit Cost Information

As part of the calculations, the benefit and cost information will also be available to the user, for each enforcement strategy at each work zone. This gives the user a straightforward look into the behind the scene mechanism and also makes user override easier.

In the "RESULT 2" window, the estimated crash frequency for each month and the entire year could be found for each work zone. Also, the user can find the CMFs, the safety benefit, and the enforcement cost, for each work zone and each strategy.

5.6 Final Notes on the Optimizer

While many assumptions have been used while developing this Optimizer, the Purdue Research Team has been consistently conservative in terms of the calculation of benefits. For example, when choosing the exponents for the Power Model, the mean estimate was used while it is reasonable to assume such exponents could be higher for high risk locations, such as work zones. Also, the effectiveness of police enforcement is applied only to the hours when enforcement is ongoing, assuming no lasting effect at all. State averages were used for crash cost while higher costs could be expected in work zones. Finally, only direct crash costs were considered while a great amount of operational cost and liability cost, both to the road user and the agency, were not included. The calculation of enforcement cost is rather straightforward and not many assumptions were made. Thus, even though the benefit/cost ratio might be lower than 1, this does not necessarily suggest the enforcement is not cost-effective.

6. CONCLUSION

In order to develop the work zone Police Enforcement Programming Tool (PEPT) for INDOT, the Purdue Research Team conducted a series of research efforts. To understand what affects work zone safety, the Purdue Research Team studied the current body of literature, assembled a comprehensive dataset, and estimated models for work zone crash prediction. To evaluate the effectiveness of police enforcement strategies in work zones, the Purdue Research Team carried out an extensive literature review, designed field experiments to evaluate the effect of selected enforcement strategies on drivers' behavior in work zones, and developed speed models incorporating the effect of police enforcement. The estimated speed reductions were used to derive CMFs that express the effect of the police enforcement strategy on work zone safety. Finally, the Purdue Research Team combined all of the developed components in a method of predicting the costs and the safety benefits in works zones under various enforcement strategies. This last method was included in the optimization tool for programming police enforcement in a group of planned work zones. The major findings and highlights of the study are summarized in this chapter.

6.1 Current Knowledge

The literature study consisted of two major sections: 1) work zone safety modeling and 2) evaluation of work zone police enforcement. The Purdue Research Team used what it learned from the literature review as guidance for the current study, which can be summarized as follows:

- Crash rates during a construction period tend to be considerably higher than before the construction period;
- Crash severity is also likely to increase during a construction period, but only a few studies could show any statistical significance;
- Work zone characteristics such as lane closure, crossover, and high construction intensity tend to increase the crash rate;
- Traffic characteristics and driver behavior were identified as contributing factors of safety in work zones.

However, more importantly, limitations were identified from the current body of literature as summarized below:

- Few work zone crash models included both a reasonably large sample size and detailed work zone features;
- There is a lack of systematic comparison of different police enforcement strategies in highway work zones;
- In the best recognized link between speed reduction and crash reduction, the Power Model, the work zone is not a specific consideration.

The Purdue Research Team made an effort to solve these issues throughout this project. The first issue was addressed by the survey of INDOT project engineers, and the second issue was reasonably solved by the enforcement experiment. There is no resource for and is out of the scope of this project to solve the third issue and future study is therefore needed.

6.2 Work Zone Crash Modeling

The following primary sources of data allowed developing a crash frequency model in work zones:

- The INDOT project engineer survey was conducted by the Purdue Research Team. This effort resulted in a dataset for 72 work zones represented by detailed cross-section geometry and traffic management information.
- The INDOT project engineer survey and the ISP enforcement log provided the opportunity to include police enforcement variables in the developed crash model.

The unprecedented dataset with detailed monthly data and the use of the random effect models led to a model that produces reliable estimation of work zone safety as demonstrated in this study provides for the first time a model that satisfies having both a sufficient number of observations and detailed data requirements.

6.3 Evaluation of Police Enforcement Strategies

The second major component of this study was evaluation of the selected police enforcement strategies. Subject to the budget constraint, the Purdue Research Team conducted a relatively small-scale, but carefully designed field evaluation of a selected set of enforcement strategies. The field activities were designed using techniques from experiment design, and the collected data were analyzed using Multilevel Model. Our concern with statistical techniques ensured the results are theoretically sound. This research effort yielded the following outcomes:

- The carefully designed field experiments evaluated several police enforcement strategies supplemented with the VMS to reinforce the motorists' awareness of the enforcement;
- The stationary police patrol and, particularly, the VMS were identified as effective methods of speed reduction;
- The effectiveness of police enforcement and VMS significantly depend on their locations with regard to the work zone segment;
- Crash Modification Factors were developed for different enforcement strategies.

6.4 Work Zone Enforcement Programming Tool

The problem of maximizing the safety benefits of the work zone police enforcement under the resources constraints including the annual budget, the number of police patrol cars available simultaneously, and the number of the VMS units available simultaneously was formulated as an integer linear programming. The solution yields, on a monthly basis, the work zones to be enforced, the police enforcement strategy, and the use of VMS units. This programming tool is implemented as a Microsoft Excel spreadsheet supplemented with the OpenSolver add-in. The tool is flexible, straightforward, and easy to use. The user should be able to quickly become familiar with the required input, results, and obtained solution.

6.5 Limitations and Future Study

The major limitations of the presented study and the results along with suggestions for future study are as follows:

- Although the collected data was as comprehensive as possible given the research resources and available data, it was found insufficient to investigate crash severity. Thus, the future research should include the effect of police enforcement on crash severity in work zones.
- Due to the budget constraint, the field evaluation of police enforcement strategies was limited to six work zones. Although the careful experimental design allowed us to incorporate all of the police enforcement strategies at each of the work zones, the variability of work zone characteristics was not sufficiently represented in the assembled sample.
- Due to the limited data, only two crash severity levels were considered in the crash cost estimation.
- The speed reduction was transferred to crash reduction using the Power Model. While the Power Model was derived from meta-analysis of more than 100 studies, its limitations for urban conditions is known. Work zone conditions are not included yet. A better linkage of the speed with the crash severity estimated with Indiana work zone data would be beneficial.

6.6 Summary

Presented in this report is a comprehensive effort by the Purdue University, Center for Road Safety research team. Greater understanding of work zone safety and police enforcement were achieved through this project, which was then packaged into a user-friendly yet powerful programming tool for ease of implementation. The Work Zone Police Enforcement Programming Tool is believed to be a significant step forward to improve work zone safety.

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APPENDIX 1. SAMPLE PROJECT ENGINEER SURVEY

Indiana Work Zone Survey

Identification Information			
Contract Num	____________	Total Award	____________
County	____________	District	____________
Letting Date	____________	Contractor	____________

Construction Phase		First Phase	Second Phase	Third Phase	Fourth Phase
Starting Date	Year				
	Month				
	Week of Month (1,2,3, or 4)				
Ending Date	Year				
	Month				
	Week of Month (1,2,3, or 4)				
Directions Affected by Work (1 or 2)					
Number of Lanes Open to Traffic					

Work Zone Features	Traffic Direction											
	First Phase			Second Phase			Third Phase			Fourth Phase		
	None	One	Both	None	One	Both	None	One	Both	None	One	Both
Traffic Detour Signs												
New Pavement												
Temporary Barrier(s)												
Traffic on Shoulder(s)												
Lanes Shift												
Lanes Split												
Police Enforcement: a, b, c, or n												

For police enforcement: a = conspicuous and ticketing, b = Conspicuous and non-ticketing, c = inconspicuous and ticketing, n = no enforcement

Name: ________________________ Date: ____________

Phone: ________________ Email: ________________

APPENDIX 2. INTERIM IMPLEMENTATION TOOL

The prioritization method currently used by INDOT is point-based and relies on expert knowledge. Points were assigned to work zone features and crash history, which reflect the expert-perceived importance of these elements for the safety benefits generated by police enforcement. These points are then weighted, rescaled, summed up, and the final scores are used to rank the candidate work zones. This intermediate implementation incorporate the preliminary findings of the SPR-3529 at the end of the first 12-month period of the study, and the method could be incorporated with the current methods used by INDOT.

By the end of the first 12 months of this study, the work zone crash modeling was finished (presented in Sections 3.2.2 and 3.2.3). Presented in Section 3.2.3 is the work zone level crash frequency modeling estimated specifically for the implementation purpose, due to the minimum requirement for data processing and the low effort of implementation, as all the data needed to implement that model are readily available from existing database.

Based on the work zone level crash frequency model, the crash frequency could be estimated using the following equation (for work zone without police enforcement):

$A = 0.0867 \cdot L^{1.046} \cdot (M \cdot V)^{1.036} \cdot \exp(0.888 \cdot U - 2.59 \cdot P + 0.415 \cdot CL - 0.0592 \cdot LS - 0.00383 \cdot RW + 0.267 \cdot SH + 0.886 \cdot HI)$,

where:

A = expected number of accidents during the construction period

L = work segment length (mi)

M = number of months

V = average ADT during the construction period in 1000s veh/day

U = fraction of the work zone length in an urban area

P = fraction of the work zone length with a parking lane before the construction period

CL = fraction of the work zone length on a collector road

LS = average width of the left shoulder (ft)

RW = average width of the right of way (ft)

SH = 1 if traffic lanes shift in the work zone; = 0, otherwise

HI = 1 if the high work intensity (construction cost > \$35,000/day/mi); =0 otherwise

Our work zone crash analysis indicates that the work zones with police enforcement experienced 55% less crashes (based on the simplified work zone level model) than other work zones if all other known safety factors were controlled. The above model can be used to supplement the scores obtained from the current method in the following way:

Calculate the expected number of crashes A in each candidate work zone using the above equation.

Calculate the safety benefit expressed with the total cost of saved crashes:

B= 0.55·\$20,000·A

The average cost of a crash on Indiana interstates and state roads is \$20,000 (calculated based on the 2011 5% report).

Calculate the cost of the police enforcement (\$38/hour of enforcement is assumed). The following formula is used:

C = \$38/hr·8 hrs/day·24 days/month·M

where M is the construction period in months.

Calculate the (B/C) ratio for each work zone.

Rescale the (B/C) ratio and add to the INDOT score.

Use the total score to select work zones for police enforcement.

Example calculations are made for eight works zone selected from the past rank list. Work zones on the top, middle and end of the list were taken. They are presented in Table A.2.1. Table A.2.2 shows the calculation of the (B/C) value.

Table A.2.3 presents one method of rescaling the B/C values and combining them with the INDOT scores. In the presented case, the B/C values are rescaled to match the highest score with the highest B/C. The following equation was used:

$$\text{Rescaled}(B/C) = \frac{\text{Max(INDOT Score)}}{\text{Max}(B/C)} \cdot \text{Original}(B/C)$$

TABLE A.2.1
Input to Calculating the Expected Number of Crashes in Construction Zones

Project ID	Work Zone Length L (mi)	Number of Months M	ADT (1000 veh/day)	Proportion in Urban Area U	Parking Lane P	Collector Road CL	Left Shoulder Width LS (ft)	Right of Way Width RW (ft)	Lanes Shift	High Intensity Work
B-27786	0.6	15	2.2	0	0	0	1	230	1	0
IR-25273	6.1	7	18.2	0.5	0	0	11	120	1	0
IR-27001	4.2	7	13.4	0	0	0	11	100	1	0
IR-29900	0.5	9	40.3	0	0	0	3	230	0	1
IR-30020	1.9	10	112.6	1	0	0	10	340	1	1
IR-30294	2.7	7	36.3	1	0	0	2	60	1	0
R-28970	9.6	7	10.5	0	0	0	11	350	1	0
R-30149	14.2	1	23.4	0	0	0	4	230	1	0

TABLE A.2.2
Calculated (B/C) for the Example Work Zones

Project ID	Predicted Crashes A	Crashes Saved (0.55*A)	Safety Benefit ($1000)	Number of Enforcement Hours	Enforcement Cost ($1000)	B/C
B-27786	0.88	0.49	9.7	2880	109.4	0.1
IR-25273	58.22	32.02	640.5	1344	51.1	12.5
IR-27001	19.69	10.83	216.6	1344	51.1	4.2
IR-29900	15.88	8.73	174.7	1728	65.7	2.7
IR-30020	285.8	157.2	3143.4	1920	73.0	43.1
IR-30294	170.10	93.56	1871.1	1344	51.1	36.6
R-28970	14.09	7.75	155.0	1344	51.1	3.0
R-30149	15.57	8.56	171.2	192	7.3	23.5

TABLE A.2.3
Combining the INDOT Scores with (B/C) Values

Project ID	INDOT Score	Calculated B/C	Rescaled B/C	Total Score	INDOT Rank	B/C Rank	Combined Rank
B-27786	1.88	0.1	0.01	1.89	8	8	8
IR-25273	2.39	12.5	1.05	3.44	7	4	5
IR-27001	3.63	4.2	0.35	3.98	1	5	4
IR-29900	3.28	2.7	0.23	3.51	2	7	6
IR-30020	3.13	43.1	3.63	6.76	3	1	1
IR-30294	3.12	36.6	3.08	6.20	4	2	2
R-28970	3.00	3.0	0.25	3.25	5	6	7
R-30149	2.85	23.5	1.98	4.83	6	3	3
Max	**3.63**	**43.10**	**3.63**	**6.76**			

APPENDIX 3. POLICE ENFORCEMENT ACTIVITY LOG

TABLE A.3.1
Detail Police Enforcement Log on May 16, 2011, at "Tippecanoe Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	VMS	VMS-Dist
51601	9:59:45 AM	10:03:00 AM	Patrolling	N/A	off	2
51602	10:03:00 AM	10:19:00 AM	Sitting-off[3]	N/A	off	2
51603	10:19:00 AM	10:20:00 AM	Patrolling	N/A	off	2
51604	10:20:00 AM	10:28:30 AM	Sitting-off	N/A	off	2
51605	10:28:30 AM	10:35:20 AM	Patrolling	N/A	off	2
51606	10:35:20 AM	11:39:00 AM	Sitting-off	N/A	off	2
51607	11:40:00 AM	11:41:00 AM	Chasing	N/A	off	2
51608	11:41:00 AM	10:45:15 AM	Sitting-on[3]	N/A	off	2
51609	10:45:15 AM	10:50:00 AM	Sitting-on	Sitting-off	off	2
51610	10:50:00 AM	10:55:30 AM	Sitting-on	Chasing	off	2
51611	10:55:30 AM	10:59:40 AM	Sitting-on	Sitting-off	off	2
51612	10:59:40 AM	11:04:40 AM	Sitting-on	Chasing	off	2
51613	11:04:40 AM	11:10:10 AM	Sitting-on	Sitting-off	off	2
51614	11:10:10 AM	11:27:55 AM	Sitting-on	Chasing	off	2
51615	11:27:55 AM	11:33:50 AM	Sitting-on	Sitting-off	off	2
51616	11:33:50 AM	11:40:45 AM	Sitting-on	Chasing	off	2
51617	11:40:45 AM	11:47:40 AM	Sitting-on	Sitting-off	off	2
51618	11:47:40 AM	11:48:50 AM	Sitting-on	Chasing	off	2
51619	11:48:50 AM	11:55:40 AM	Sitting-on	Sitting-off	off	2
51620	11:55:40 AM	12:17:45 PM	Sitting-on	Chasing	off	2
51621	12:17:45 PM	12:24:00 PM	Sitting-on	Sitting-off	off	2
51622	12:24:00 PM	12:26:30 PM	Sitting-on	Chasing	off	2
51623	12:26:30 PM	12:43:45 PM	Sitting-on	Sitting-off	off	2
51624	12:43:45 PM	12:49:10 PM	Sitting-on	Chasing	off	2
51625	12:49:10 PM	1:07:05 PM	Sitting-on	Sitting-off	off	2
51626	1:07:05 PM	1:25:00 PM	Sitting-on	N/A	off	2
51627	1:25:00 PM	1:59:00 PM	Chasing	N/A	off	2
51628	1:59:00 PM	2:09:00 PM	Sitting-on	N/A	off	2
51629	2:09:00 PM	2:40:00 PM	Chasing	N/A	off	2
51630	2:40:00 PM	3:00:00 PM	N/A	N/A	off	2
51631	3:00:00 PM	3:26:10 PM	Sitting-on	N/A	off	2
51632	3:26:10 PM	4:19:00 PM	Chasing	N/A	off	2

[1]Car-1 is stationed at the start of the work zone.
[2]Car-2 is stationed at the start of the actual activity area, 0.65 mile into the work zone.
[3]On/Off indicates the emergency lights are on or off, since officers refused to turn the lights on for the entire activity time.

TABLE A.3.2
Detail Police Enforcement Log on May 18, 2011, at "Tippecanoe Work Zone"

ID-EFC	Start	End	Car-1&3[1]	Car-2[2]	VMS	VMS-Dist
51801	9:52:10 AM	9:54:30 AM	Patrolling	N/A	off	2
51802	9:54:30 AM	9:58:20 AM	Patrolling	N/A	off	2
51803	10:04:30 AM	10:05:30 AM	Patrolling	N/A	on	2
51804	10:05:30 AM	10:15:00 AM	Sitting-off[3]	N/A	on	2
51805	10:15:00 AM	10:16:30 AM	Patrolling	N/A	on	2
51806	10:17:00 AM	10:21:00 AM	Sitting-off	N/A	on	2
51807	10:22:00 AM	10:22:45 AM	Chasing	N/A	on	2
51808	10:34:45 AM	10:35:30 AM	Patrolling	N/A	on	2
51809	10:36:00 AM	12:58:00 PM	Sitting-on[3]	N/A	on	2
51810	12:58:00 PM	1:25:00	N/A	N/A	on	2
51811	1:25:00	1:39:00	Sitting-off	Sitting-off	on	2
51812	1:39:00	1:45:45	Chasing	Sitting-off	on	2
51813	2:07:00	2:24:00	Patrolling	Sitting-off	on	2
51814	2:24:00	2:28:30	Sitting	Sitting-off	on	2
51815	2:28:30	2:35:00	Chasing	Sitting-off	on	2
51816	2:35:00	2:39:30	Patrolling	Sitting-off	on	2
51817	2:39:39	2:45:00	Sitting	Sitting-off	on	2
51818	2:45:00	2:49:00	Chasing	Sitting-off	on	2
51819	2:49:00	2:54:30	Patrolling	Chasing	on	2
51820	2:54:30	3:00:00	Sitting	Chasing	on	2
51821	3:00:00	3:02:30	Sitting	Sitting	on	2
51822	3:02:30	3:16:00	Chasing	Sitting	on	2
51823	3:16:00	3:24:00	Sitting	Sitting	on	2
51824	3:24:00	3:25:00	Sitting	Chasing	on	2
51825	3:25:00	3:33:30	Chasing	Chasing	on	2
51826	3:33:30	3:40:45	Sitting	Chasing	on	2
51827	3:40:45	3:45:30	Chasing	Chasing	on	2
51828	3:45:30	3:50:45	Sitting	Chasing	on	2
51829	3:50:45	3:52:00	Chasing	Chasing	on	2
51830	3:52:00	3:58:00	Patrolling	Sitting	on	2
51831	3:58:00	4:21:00	N/A	Sitting	on	2

[1]Car-1 and Car-3 are stationed at the start of the work zone.
[2]Car-2 is stationed at the start of the actual activity area, 0.65 mile into the work zone.
[3]On/Off indicates the emergency lights are on or off, since officers refused to turn the lights on for the entire activity time.

TABLE A.3.3
Detail Police Enforcement Log on June 9, 2011, at "Greenfield Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	Car-3[3]	Car-4[4]	VMS	VMS-Dist
60901	9:44:00 AM	9:49:15 AM	N/A	N/A	Sitting	N/A	off	1.8
60902	9:49:15 AM	10:43:45 AM	N/A	Sitting	Sitting	N/A	off	1.8
60903	10:43:45 AM	10:46:00 AM	N/A	Patrolling	Sitting	N/A	off	1.8
60904	10:46:00 AM	11:03:15 AM	N/A	N/A	Sitting	N/A	off	1.8
60905	11:03:15 AM	11:30:00 AM	N/A	Sitting	Sitting	N/A	off	1.8
60905	11:30:00 AM	11:40:45 AM	N/A	Sitting	Sitting	N/A	on	1.8
60906	11:40:45 AM	11:49:45 AM	N/A	Sitting	N/A	N/A	on	1.8
60907	11:49:45 AM	12:59:15 PM	N/A	Sitting	Sitting	N/A	on	1.8
60908	12:59:15 PM	1:03:45 AM	N/A	Sitting	N/A	N/A	on	1.8
60909	1:03:45 AM	1:49:00 PM	N/A	N/A	N/A	N/A	off	1.8
60910	1:49:00 PM	1:53:30 PM	Sitting	N/A	N/A	N/A	off	1.8
60911	1:53:30 PM	1:54:45 PM	Sitting	N/A	N/A	Sitting	off	1.8
60912	1:54:45 PM	1:55:45 PM	Sitting	N/A	Patrolling	Sitting	off	1.8
60913	1:55:45 PM	2:00:00 PM	Sitting	N/A	Sitting	Sitting	off	1.8
60913	2:00:00 PM	2:04:00 PM	Sitting	N/A	Sitting	Sitting	on	1.8
60914	2:04:00 PM	3:08:30 PM	Sitting	Sitting	Sitting	Sitting	on	1.8
60915	3:08:30 PM	3:13:00 PM	Sitting	Sitting	Patrolling	Sitting	on	1.8
60916	3:13:00 PM	3:32:15 PM	Sitting	Sitting	N/A	Sitting	on	1.8
60917	3:32:15 PM	3:33:45 PM	Sitting	Sitting	Patrolling	Sitting	off	1.8
60918	3:33:45 PM	4:32:30 PM	Sitting	Sitting	Sitting	Sitting	off	1.8
60919	4:32:30 PM	4:35:00 PM	Sitting	Patrolling	Sitting	Sitting	off	1.8
60920	4:35:00 PM	4:37:30 PM	Sitting	N/A	Sitting	Sitting	off	1.8
60921	4:37:30 PM	4:52:45 PM	Sitting	N/A	Sitting	N/A	off	1.8
60922	4:52:45 PM	4:53:00 PM	Patrolling	N/A	Sitting	N/A	off	1.8
60923	4:53:00 PM	4:56:00 PM	Patrolling	N/A	Patrolling	N/A	off	1.8
60924	4:56:00 PM	4:56:30 PM	Patrolling	N/A	N/A	N/A	off	1.8

[1]Car-1 is stationed upstream of the work zone, 2.3 miles from the start of the work zone.
[2]Car-2 is stationed at the start of the work zone.
[3]Car-3 is stationed inside the work zone, 2.8 miles from the start of the work zone.
[4]Car-4 is stationed at the end of the work zone.

TABLE A.3.4
Detail Police Enforcement Log on July 14, 2011, at "Greenfield Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	Car-3[3]	Car-4[4]	VMS	VMS-Dist
71401	9:49:00 AM	9:54:30 AM	N/A	N/A	Sitting	N/A	off	1.8
71402	9:54:30 AM	10:00:00 AM	N/A	Sitting	Sitting	N/A	off	1.8
71402	10:00:00 AM	10:03:00 AM	N/A	Sitting	Sitting	N/A	on	1.8
71403	10:03:00 AM	11:28:30 AM	Sitting	Sitting	Sitting	N/A	on	1.8
71404	11:28:30 AM	11:31:30 AM	Patrolling	Sitting	Sitting	N/A	on	1.8
71405	11:31:30 AM	11:34:45 AM	N/A	Sitting	Sitting	N/A	off	1.8
71406	11:34:45 AM	11:36:15 AM	N/A	Patrolling	Sitting	N/A	off	1.8
71407	11:36:15 AM	11:47:30 AM	N/A	N/A	Sitting	N/A	off	1.8
71408	11:47:30 AM	11:48:00 AM	Sitting	N/A	Sitting	N/A	off	1.8
71409	11:48:00 AM	12:39:30 PM	Sitting	Sitting	Sitting	N/A	off	1.8
71410	12:39:30 PM	12:56:30 PM	Sitting	Sitting	N/A	N/A	off	1.8
71411	12:56:30 PM	12:57:30 PM	Sitting	N/A	N/A	N/A	off	1.8
71412	12:57:30 PM	1:58:30 PM	N/A	N/A	N/A	N/A	off	1.8
71413	1:58:30 PM	2:10:00 PM	N/A	N/A	Sitting	N/A	off	1.8
71414	2:10:00 PM	3:30:00 PM	N/A	Sitting	Sitting	N/A	off	1.8
71414	3:30:00 PM	3:53:30 PM	N/A	Sitting	Sitting	N/A	on	1.8
71415	3:53:30 PM	3:58:00 PM	N/A	Sitting	Patrolling	N/A	on	1.8
71416	3:58:00 PM	4:05:00 PM	N/A	Sitting	N/A	N/A	on	1.8
71417	4:05:00 PM	4:10:00 PM	N/A	Patrolling	N/A	N/A	on	1.8
71418	4:10:00 PM	4:20:00 PM	N/A	Patrolling	Patrolling	N/A	on	1.8
71419	4:20:00 PM	4:21:30 PM	N/A	N/A	Patrolling	N/A	on	1.8

[1]Car-1 is stationed upstream of the work zone, 2.3 miles from the start of the work zone;
[2]Car-2 is stationed at the start of the work zone.
[3]Car-3 is stationed inside the work zone, 2.8 miles from the start of the work zone.
[4]Car-4 is stationed at the end of the work zone.

TABLE A.3.5
Detail Police Enforcement Log on June 21, 2011, at "Airport Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	Car-3[3]	Car-4[4]	VMS	VMS-Dist
62101	9:45:54	9:59:22	Sitting	N/A	N/A	N/A	off	1.95
62102	9:59:22	10:37:01	Sitting	N/A	N/A	Sitting	on	1.95
62103	10:37:01	10:40:05	Sitting	Sitting	N/A	Sitting	on	1.95
62104	10:40:05	11:30:00	Sitting	Sitting	N/A	Sitting	on	1.95
62104	11:30:00	12:49:21	Sitting	Sitting	N/A	Sitting	off	1.95
62105	12:49:21	12:56:23	Sitting	Sitting	N/A	N/A	off	1.95
62106	12:56:23	12:58:45	Patrolling	Sitting	N/A	N/A	off	1.95
62107	12:58:45	13:01:25	N/A	Sitting	N/A	N/A	off	1.95
62108	13:01:25	14:14:34	N/A	N/A	N/A	N/A	off	1.95
62109	14:14:34	14:35:32	N/A	Sitting	N/A	N/A	off	1.95
62110	14:35:32	14:58:35	N/A	Sitting	Sitting	N/A	off	1.95
62111	14:58:35	15:06:14	N/A	Sitting	N/A	N/A	off	1.95
62112	15:06:14	15:30:00	Sitting	Sitting	N/A	N/A	off	1.95
62112	15:30:00	16:45:20	Sitting	Sitting	N/A	N/A	on	1.95
62113	16:45:20	16:55:00	Sitting	N/A	N/A	N/A	on	1.95

[1]Car-1 is stationed at the start of the work zone.
[2]Car-2 is stationed inside the work zone, 0.95 miles from the start of the work zone.
[3]Car-3 is stationed inside the work zone, 1.85 miles from the start of the work zone.
[4]Car-4 is stationed at the end of the work zone.

TABLE A.3.6
Detail Police Enforcement Log on June 23, 2011, at "Airport Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	Car-3[3]	Car-4[4]	VMS	VMS-Dist
62301	10:08:59	10:09:57	N/A	Sitting	N/A	N/A	off	1.95
62302	10:09:57	11:30:00	N/A	Sitting	Sitting	N/A	off	1.95
62302	11:30:00	12:46:08	N/A	Sitting	Sitting	N/A	on	1.95
62303	12:46:08	12:50:41	N/A	Sitting	N/A	N/A	on	1.95
62304	12:50:41	13:49:11	N/A	N/A	N/A	N/A	off	1.95
62305	13:49:11	13:55:16	Sitting	N/A	N/A	N/A	off	1.95
62306	13:55:16	14:19:00	Sitting	N/A	N/A	Sitting	on	1.95
62307	14:19:00	15:30:00	Sitting	Sitting	N/A	Sitting	on	1.95
62307	15:30:00	16:10:31	Sitting	Sitting	N/A	Sitting	off	1.95
62308	16:10:31	16:25:04	N/A	Sitting	N/A	Sitting	off	1.95
62309	16:25:04	end of recording	N/A	Sitting	N/A	N/A	off	1.95

[1]Car-1 is stationed at the start of the work zone.
[2]Car-2 is stationed inside the work zone, 0.95 miles from the start of the work zone.
[3]Car-3 is stationed inside the work zone, 1.85 miles from the start of the work zone.
[4]Car-4 is stationed at the end of the work zone.

TABLE A.3.7
Detail Police Enforcement Log on July 19, 2011, at "South Bend Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]
71901	10:00:00 AM	10:30:13 AM	Two car	N/A
71902	10:30:13 AM	10:34:06 AM	Sitting	N/A
71903	10:34:06 AM	12:49:23 PM	Sitting	Sitting
71904	12:49:23 PM	12:59:00 PM	Sitting	N/A
71905	12:59:00 PM	2:04:00 PM	N/A	N/A
71906	2:04:00 PM	4:39:36 PM	Sitting	N/A

[1]Car-1 is stationed at the start of the work zone.
[2]Car-2 is stationed at the start of the actual activity area, 0.3 mile into the work zone.
NOTE: VMS is not planned for this work zone since it is on a non-access controlled road.

TABLE A.3.8
Detail Police Enforcement Log on July 20, 2011, at "South Bend Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]
72001	10:06:00 AM	12:42:43 PM	Sitting	N/A
72002	12:42:46 PM	1:24:10 PM	N/A	Sitting
72003	1:24:10 PM	1:57:13 PM	N/A	N/A
72004	1:57:13 PM	2:11:41 PM	Sitting	N/A
72005	2:11:41 PM	2:33:20 PM	Sitting	Sitting
72006	2:33:20 PM	2:59:00 PM	Sitting	N/A
72007	2:59:00 PM	3:03:47 PM	Sitting	Sitting
72008	3:03:47 PM	3:10:48 PM	Sitting	N/A

[1]Car-1 is stationed at the start of the work zone.
[2]Car-2 is stationed at the start of the actual activity area, 0.3 mile into the work zone.
NOTE: VMS is not planned for this work zone since it is on a non-access controlled road.

TABLE A.3.9
Detail Police Enforcement Log on October 21, 2011, at "Fishers Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	VMS	VMS-Dist
102101	10:25:00	10:26:30	Patrolling	Patrolling	on	1.25
102102	10:26:30	11:30:00	Sitting	Sitting	on	1.25
102102	11:30:00	12:45:00	Sitting	Sitting	off	1.25
102103	12:45:00	13:59:50	N/A	N/A	off	1.25
102104	13:59:50	14:01:30	Patrolling	N/A	off	1.25
102105	14:01:30	15:30:00	Sitting	N/A	off	1.25
102105	15:30:00	16:45:00	Sitting	N/A	on	1.25

[1]Car-1 is stationed at the start of the work zone.
[2]Car-2 is stationed at the start of the advance warning area, 1 mile upstream of the work zone.

TABLE A.3.10
Detail Police Enforcement Log on October 25, 2011, at "Fishers Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	VMS	VMS-Dist
102501	10:15:05	10:16:30	Patrolling	N/A	off	1.25
102502	10:16:30	11:30:00	Sitting	N/A	off	1.25
102502	11:30:00	12:56:40	Sitting	N/A	on	1.25
102503	12:56:40	1:57:20	N/A	N/A	off	1.25
102504	1:57:20	1:59:15	Sitting	Patrolling	off	1.25
102505	1:59:15	3:30:00	Sitting	Sitting	on	1.25
102505	3:30:00	4:40:40	Sitting	Sitting	off	1.25
102506	4:40:40	4:42:30	N/A	Sitting	off	1.25

[1]Car-1 is stationed at the start of the work zone.
[2]Car-2 is stationed at the start of the advance warning area, 1 mile upstream of the work zone.

TABLE A.3.11
Detail Police Enforcement Log on November 8, 2011, at "Terre Haute Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	Car-3[3]	Car-4[4]	VMS	VMS-Dist
110801	10:43:30	10:46:50	Sitting	Patrolling	Patrolling	Patrolling	on	12.8
110802	10:46:50	10:51:00	Sitting	Sitting	Patrolling	Patrolling	on	12.8
110803	10:51:00	10:56:20	Sitting	Sitting	Sitting	Patrolling	on	12.8
110804	10:56:20	11:30:00	Sitting	Sitting	Sitting	Sitting	on	12.8
110804	11:30:00	12:46:25	Sitting	Sitting	Sitting	Sitting	off	12.8
110807	13:00:00	1:56:10	N/A	N/A	N/A	N/A	off	12.8
110808	1:56:10	1:58:40	N/A	Patrolling	N/A	N/A	off	12.8
110809	1:58:40	2:03:20	N/A	Sitting	N/A	N/A	off	12.8
110810	2:03:20	2:10:30	N/A	Sitting	Patrolling	N/A	off	12.8
110811	2:10:30	3:30:00	N/A	Sitting	Sitting	N/A	off	12.8
110811	3:30:00	4:30:15	N/A	Sitting	Sitting	N/A	on	12.8
110812	4:30:15	4:46:15	N/A	Sitting	N/A	N/A	on	12.8

[1]Car-1 is stationed upstream of the work zone, 1.28 miles from the start of work zone.
[2]Car-2 is stationed at the start of the work zone.
[3]Car-3 is stationed inside the work zone, 2.6 miles from the start of the work zone.
[4]Car-4 is stationed at the end of the work zone.

TABLE A.3.12
Detail Police Enforcement Log on November 11, 2011, at "Terre Haute Work Zone"

ID-EFC	Start	End	Car-1[1]	Car-2[2]	Car-3[3]	Car-4[4]	VMS	VMS-Dist
111101	10:23:40	10:24:00	Patrolling	N/A	N/A	N/A	off	−2.4
111102	10:24:00	10:25:55	Patrolling	N/A	Patrolling	N/A	off	−2.4
111103	10:25:55	10:26:50	Patrolling	N/A	Sitting	N/A	off	−2.4
111104	10:26:50	11:30:00	Sitting	N/A	Sitting	N/A	off	−2.4
111104	11:30:00	12:39:00	Sitting	N/A	Sitting	N/A	on	−2.4
111105	12:39:00	12:45:00	Sitting	N/A	N/A	N/A	on	−2.4
111106	12:45:00	12:50:10	Patrolling	N/A	N/A	N/A	on	−2.4
111107	12:50:10	2:06:30	N/A	N/A	N/A	N/A	off	−2.4
111108	2:06:30	2:09:15	N/A	N/A	N/A	Patrolling	on	−2.4
111109	2:09:15	2:15:35	N/A	N/A	Sitting	Sitting	on	−2.4
111110	2:15:35	2:16:40	N/A	N/A	Sitting	Sitting	on	−2.4
111111	2:16:40	2:18:00	Sitting	N/A	Sitting	Sitting	on	−2.4
111112	2:18:00	3:27:30	Sitting	Sitting	Sitting	Sitting	on	−2.4
111113	3:27:30	3:31:55	Sitting	Sitting	Sitting	Sitting	on	−2.4
111114	3:31:55	3:33:20	Patrolling	Sitting	Sitting	Sitting	off	−2.4
111115	3:33:20	3:35:30	Patrolling	Patrolling	Sitting	Sitting	off	−2.4
111116	3:35:30	3:38:30	Patrolling	Patrolling	Sitting	Sitting	off	−2.4
111117	3:38:30	3:57:00	N/A	N/A	Sitting	Two Car	off	−2.4
111118	3:57:00	3:58:00	N/A	Sitting	Sitting	Two Car	off	−2.4
111119	3:58:00	4:03:00	N/A	Sitting	Patrolling	Two Car	off	−2.4
111120	4:03:00	4:04:00	N/A	Patrolling	Patrolling	Two Car	off	−2.4
111121	4:04:00	4:07:25	N/A	N/A	Patrolling	Two Car	off	−2.4
111122	4:07:25	4:38:00	N/A	N/A	N/A	Two Car	off	−2.4
111123	4:38:00	4:40:40	N/A	Patrolling	N/A	Two Car	off	−2.4
111124	4:40:40	4:41:00	N/A	Patrolling	N/A	Sitting	off	−2.4
111125	4:41:00	4:42:00	N/A	Patrolling	N/A	Sitting	off	−2.4

[1]Car-1 is stationed upstream of the work zone, 1.05 miles from the start of the work zone.
[2]Car-2 is stationed at the start of the work zone.
[3]Car-3 is stationed inside the work zone, 2 miles from the start of the work zone in the morning period and 2.4 miles from the start of the work zone in the afternoon period.
[4]Car-4 is stationed at the end of the work zone and s two police vehicles are present after 3:30 pm due to crashes.

TABLE A.4.1
Detail Police Enforcement Activities on May 16, 2011, at "Tippecanoe Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chase	Dist-before	Dist-in	Dist-in-2	Light-1	Light-2
51601	off	0	0	0	0	0	1	0	0	0	0	0	0
51602	off	0	0	1	0	0	0	0	0	0	0	0	0
51603	off	0	0	0	0	0	1	0	0	0	0	0	0
51604	off	0	0	1	0	0	0	0	0	0	0	0	0
51605	off	0	0	0	0	0	1	0	0	0	0	1	0
51606	off	0	0	1	0	0	0	0	0	0	0	0	0
51607	off	0	0	0	0	0	0	1	0	0	0	1	0
51608	off	0	0	1	0	0	0	0	0	0	0	1	0
51609	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51610	off	0	0	1	0	0	0	1	0	0	0	1	1
51611	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51612	off	0	0	1	0	0	0	1	0	0	0	1	1
51613	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51614	off	0	0	1	0	0	0	1	0	0	0	1	1
51615	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51616	off	0	0	1	0	0	0	1	0	0	0	1	1
51617	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51618	off	0	0	1	0	0	0	1	0	0	0	1	1
51619	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51620	off	0	0	1	0	0	0	1	0	0	0	1	1
51621	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51622	off	0	0	1	0	0	0	1	0	0	0	1	1
51623	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51624	off	0	0	1	0	0	0	1	0	0	0	1	1
51625	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51626	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51627	off	0	0	0	1	0	0	1	0	0.65	0	1	0
51628	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51629	off	0	0	0	1	0	0	1	0	0.65	0	1	0
51630	off	0	0	1	1	0	0	0	0	0.65	0	0	0
51631	off	0	0	1	1	0	0	0	0	0.65	0	1	0
51632	off	0	0	0	1	0	0	1	0	0.65	0	1	0

TABLE A.4.2
Detail Police Enforcement Activities on May 18, 2011, at "Tippecanoe Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2	Light-1	Light-2
51801	off	0	0	0	0	0	1	0	0	0	0	0	0
51802	off	0	0	0	0	0	1	0	0	0	0	0	0
51803	on	2	0	0	0	0	1	0	0	0	0	0	0
51804	on	2	0	1	0	0	0	0	0	0	0	0	0
51805	on	2	0	0	0	0	1	0	0	0	0	0	0
51806	on	2	0	1	0	0	0	0	0	0	0	0	0
51807	on	2	0	0	0	0	0	1	0	0	0	1	0
51808	on	2	0	0	0	0	1	0	0	0	0	0	0
51809	on	2	0	1	0	0	0	0	0	0	0	1	0
51810	on	2	0	0	0	0	0	0	0	0	0	0	0
51811	on	2	0	1	1	0	0	0	0	0.65	0	0	0
51812	on	2	0	0	1	0	0	1	0	0.65	0	1	0
51813	on	2	0	0	1	0	1	0	0	0.65	0	0	0
51814	on	2	0	1	1	0	0	0	0	0.65	0	0	0
51815	on	2	0	0	1	0	0	1	0	0.65	0	1	0
51816	on	2	0	0	1	0	1	0	0	0.65	0	0	0
51817	on	2	0	1	1	0	0	0	0	0.65	0	0	0
51818	on	2	0	0	1	0	0	1	0	0.65	0	1	0
51819	on	2	0	0	0	0	1	1	0	0	0	0	1
51820	on	2	0	1	0	0	0	1	0	0	0	0	1
51821	on	2	0	1	1	0	0	0	0	0.65	0	0	0
51822	on	2	0	0	1	0	0	1	0	0.65	0	1	0
51823	on	2	0	1	1	0	0	0	0	0.65	0	0	0
51824	on	2	0	1	0	0	0	1	0	0	0	0	1
51825	on	2	0	0	0	0	0	1	0	0	0	1	1
51826	on	2	0	1	0	0	0	1	0	0	0	0	1
51827	on	2	0	0	0	0	0	1	0	0	0	1	1
51828	on	2	0	1	0	0	0	1	0	0	0	0	1
51829	on	2	0	0	0	0	0	1	0	0	0	1	1
51830	on	2	0	0	1	0	1	0	0	0.65	0	0	0
51831	on	2	0	0	1	0	0	0	0	0.65	0	0	0

TABLE A.4.3
Detail Police Enforcement Activities on June 9, 2011, at "Greenfield Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
60901	off	0	0	0	1	0	0	0	0	2.8	0
60902	off	0	0	1	1	0	0	0	0	2.8	0
60903	off	0	0	0	1	0	1	0	0	2.8	0
60904	off	0	0	0	1	0	0	0	0	2.8	0
60905	off	0	0	1	1	0	0	0	0	2.8	0
60906	on	1.8	0	1	1	0	0	0	0	2.8	0
60907	on	1.8	0	1	0	0	0	0	0	0	0
60908	on	1.8	0	1	1	0	0	0	0	2.8	0
60909	on	1.8	0	1	0	0	0	0	0	0	0
60910	off	0	0	0	0	0	0	0	0	0	0
60911	off	0	1	0	0	0	0	0	2.3	0	0
60912	off	0	1	0	0	1	0	0	2.3	0	0
60913	off	0	1	0	0	1	1	0	2.3	0	0
60914	off	0	1	0	1	1	0	0	2.3	2.8	0
60915	on	1.8	1	0	1	1	0	0	2.3	2.8	0
60916	on	1.8	1	1	1	1	0	0	2.3	2.8	0
60917	on	1.8	1	1	0	1	1	0	2.3	0	0
60918	on	1.8	1	1	0	1	0	0	2.3	0	0
60919	off	0	1	1	0	1	1	0	2.3	0	0
60920	off	0	1	1	1	1	0	0	2.3	2.8	0
60921	off	0	1	0	1	1	1	0	2.3	2.8	0
60922	off	0	1	0	1	1	0	0	2.3	2.8	0
60923	off	0	1	0	1	0	0	0	2.3	2.8	0
60924	off	0	0	0	1	0	1	0	0	2.8	0
60925	off	0	0	0	0	0	1	0	0	0	0
60926	off	0	0	0	0	0	1	0	0	0	0

TABLE A.4.4
Detail Police Enforcement Activities on July 14, 2011, at "Greenfield Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-Chase	Dist-before	Dist-in	Dist-in-2
71401	off	0	0	0	1	0	0	0	0	2.8	0
71402	off	0	0	1	1	0	0	0	0	2.8	0
71402	on	1.8	0	1	1	0	0	0	0	2.8	0
71403	on	1.8	1	1	1	0	0	0	2.3	2.8	0
71404	on	1.8	0	1	1	0	1	0	0	2.8	0
71405	off	0	0	1	1	0	0	0	0	2.8	0
71406	off	0	0	0	1	0	1	0	0	2.8	0
71407	off	0	0	0	1	0	0	0	0	2.8	0
71408	off	0	1	0	1	0	0	0	2.3	2.8	0
71409	off	0	1	1	1	0	0	0	2.3	2.8	0
71410	off	0	1	1	0	0	0	0	2.3	0	0
71411	off	0	1	0	0	0	0	0	2.3	0	0
71412	off	0	0	0	0	0	0	0	0	0	0
71413	off	0	0	0	1	0	0	0	0	2.8	0
71414	off	0	0	1	1	0	0	0	0	2.8	0
71415	on	1.8	0	1	1	0	0	0	0	2.8	0
71416	on	1.8	0	1	0	0	1	0	0	0	0
71417	on	1.8	0	1	0	0	0	0	0	0	0
71418	on	1.8	0	0	0	0	1	0	0	0	0
71419	on	1.8	0	0	0	0	1	0	0	0	0
71420	on	1.8	0	0	0	0	1	0	0	0	0

TABLE A.4.5
Detail Police Enforcement Activities on June 21, 2011, at "Airport Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-Chase	Dist-before	Dist-in	Dist-in-2
62101	off	0	0	1	0	0	0	0	0	0	0
62102	on	1.95	0	1	0	1	0	0	0	0	0
62103	on	1.95	0	1	1	1	0	0	0	0.95	0
62104	on	1.95	0	1	1	1	0	0	0	0.95	0
62105	off	0	0	1	1	1	0	0	0	0.95	0
62106	off	0	0	1	1	0	0	0	0	0.95	0
62107	off	0	0	0	1	0	1	0	0	0.95	0
62108	off	0	0	0	1	0	0	0	0	0.95	0
62109	off	0	0	0	0	0	0	0	0	0	0
62110	off	0	0	0	1	0	0	0	0	0.95	0
62111	off	0	0	0	2	0	0	0	0	0.95	1.85
62112	off	0	0	0	1	0	0	0	0	0.95	0
62113	off	0	0	1	1	0	0	0	0	0.95	0
62114	on	1.95	0	1	1	0	0	0	0	0.95	0
62115	on	1.95	0	1	0	0	0	0	0	0	0

TABLE A.4.6
Detail Police Enforcement Activities on June 23, 2011, at "Airport Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
62301	off	0	0	0	1	0	0	0	0	0.95	0
62302	off	0	0	0	2	0	0	0	1	0.95	1.85
62303	on	1.95	0	0	2	0	0	0	2	0.95	1.85
62304	on	1.95	0	0	1	0	0	0	3	0.95	0
62305	off	0	0	0	0	0	0	0	4	0	0
62306	off	0	0	1	0	0	0	0	5	0	0
62307	on	1.95	0	1	0	1	0	0	6	0	0
62308	on	1.95	0	1	1	1	0	0	7	0.95	0
62309	off	0	0	1	1	1	0	0	8	0.95	0
62310	off	0	0	0	1	1	0	0	9	0.95	0
62311	off	0	0	0	1	0	0	0	10	0.95	0

TABLE A.4.7
Detail Police Enforcement Activities on July 19, 2011, at "South Bend Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
71901	off	0	0	1	0	0	0	0	0	0	0
71902	off	0	0	1	0	0	0	0	0	0	0
71903	off	0	0	1	1	0	0	0	0	0.3	0
71904	off	0	0	1	0	0	0	0	0	0	0
71905	off	0	0	0	0	0	0	0	0	0	0
71906	off	0	0	1	0	0	0	0	0	0	0

TABLE A.4.8
Detail Police Enforcement Activities on July 20, 2011, at "South Bend Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
72001	off	0	0	1	0	0	0	0	0	0	0
72002	off	0	0	0	1	0	0	0	0	0.3	0
72003	off	0	0	0	0	0	0	0	0	0	0
72004	off	0	0	0	1	0	0	0	0	0.3	0
72005	off	0	0	1	1	0	0	0	0	0.3	0
72006	off	0	0	1	0	0	0	0	0	0	0
72007	off	0	0	1	1	0	0	0	0	0.3	0
72008	off	0	0	1	0	0	0	0	0	0	0

TABLE A.4.9
Detail Police Enforcement Activities on October 21, 2011, at "Fishers Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
102101	on	1.25	0	0	0	0	1	0	0	0	0
102102	on	1.25	1	1	0	0	0	0	1	0	0
102103	off	1.25	1	1	0	0	0	0	1	0	0
102104	off	1.25	0	0	0	0	0	0	0	0	0
102105	off	1.25	0	0	0	0	1	0	0	0	0
102106	off	1.25	0	1	0	0	0	0	0	0	0
102107	on	1.25	0	1	0	0	0	0	0	0	0

TABLE A.4.10
Detail Police Enforcement Activities on October 25, 2011, at "Fishers Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
102501	off	1.25	0	0	0	0	1	0	0	0	0
102502	off	1.25	0	1	0	0	0	0	0	0	0
102503	on	1.25	0	1	0	0	0	0	0	0	0
102504	off	1.25	0	0	0	0	0	0	0	0	0
102505	off	1.25	0	1	0	0	1	0	0	0	0
102506	on	1.25	1	1	0	0	0	0	1	0	0
102507	off	1.25	1	1	0	0	0	0	1	0	0
102508	off	1.25	1	0	0	0	0	0	1	0	0

TABLE A.4.11
Detail Police Enforcement Log on November 8, 2011, at "Terre Haute Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
110801	on	12.8	1	0	0	0	1	0	1.28	0	0
110802	on	12.8	1	1	0	0	1	0	1.28	0	0
110803	on	12.8	1	1	1	0	1	0	1.28	2.6	0
110804	on	12.8	1	1	1	1	0	0	1.28	2.6	0
110805	off	12.8	1	1	1	1	0	0	1.28	2.6	0
110806	off	12.8	0	0	0	0	0	0	0	0	0
110807	off	12.8	0	0	0	0	0	0	0	0	0
110808	off	12.8	0	0	0	0	0	0	0	0	0
110809	off	12.8	0	0	0	0	1	0	0	0	0
110810	off	12.8	0	1	0	0	0	0	0	0	0
110811	off	12.8	0	1	0	0	1	0	0	0	0
110812	off	12.8	0	1	1	1	0	0	0	2.6	0
110813	on	12.8	0	1	1	1	0	0	0	2.6	0
110814	on	12.8	0	1	0	0	0	0	0	0	0

TABLE A.4.12
Detail Police Enforcement Log on November 11, 2011, at "Terre Haute Work Zone"

ID-EFC	VMS	VMS-Dist	Loc-before	Loc-begin	Loc-in	Loc-end	Loc-patrol	Loc-chasing	Dist-before	Dist-in	Dist-in-2
111101	off	−2.4	0	0	0	0	1	0	0	0	0
111102	off	−2.4	0	0	0	0	1	0	0	0	0
111103	off	−2.4	0	0	1	0	1	0	0	2	0
111104	off	−2.4	1	0	1	0	0	0	1.05	2	0
111105	on	−2.4	1	0	1	0	0	0	1.05	2	0
111106	on	−2.4	1	0	0	0	0	0	1.05	0	0
111107	on	−2.4	0	0	0	0	1	0	0	0	0
111108	off	−2.4	0	0	0	0	0	0	0	0	0
111109	on	−2.4	0	0	0	0	1	0	0	0	0
111110	on	−2.4	0	0	1	1	0	0	0	2.4	0
111111	on	−2.4	0	0	1	1	0	0	0	2.4	0
111112	on	−2.4	1	0	1	1	0	0	1.05	2.4	0
111113	on	−2.4	1	1	1	1	0	0	1.05	2.4	0
111114	on	−2.4	1	1	1	1	0	0	1.05	2.4	0
111115	off	−2.4	0	1	1	1	1	0	0	2.4	0
111116	off	−2.4	0	0	1	1	1	0	0	2.4	0
111117	off	−2.4	0	0	1	1	1	0	0	2.4	0
111118	off	−2.4	0	0	1	2	0	0	0	2.4	0
111119	off	−2.4	0	1	1	2	0	0	0	2.4	0
111120	off	−2.4	0	1	0	2	1	0	0	0	0
111121	off	−2.4	0	0	0	2	1	0	0	0	0
111122	off	−2.4	0	0	0	2	1	0	0	0	0
111123	off	−2.4	0	0	0	2	0	0	0	0	0
111124	off	−2.4	0	0	0	2	1	0	0	0	0
111125	off	−2.4	0	0	0	2	1	0	0	0	0
111126	off	−2.4	0	0	0	2	1	0	0	0	0

APPENDIX 5. OPTIMIZER USER'S MANUAL

http://docs.lib.purdue.edu/cgi/viewcontent.cgi?filename=0&article=3019&context=jtrp&type=additional