ABSTRACT
Due to the aging U.S. highway system and the frequent presence of work zones, highway work zone safety is garnering increasing attention. Police enforcement is sometimes used by U.S. transportation agencies for safety improvement in work zones. The important question that must be answered by those responsible for programming police enforcement in work zones is: where, when and how to enforce? This paper presents a research conducted by the Purdue Center for Road Safety (CRS) for the Indiana Department of Transportation (INDOT) aimed to develop a tool for selecting work zones, periods of enforcement, and enforcement strategies that maximize the safety benefit within the available budget. This research included modeling of the crash frequency in work zones to better understand work zone safety factors and evaluating several police enforcement strategies through a carefully designed police enforcement experiment in selected work zones. The study has confirmed several findings of the previous studies and it has provided new results such as finding that Variable Message Sign units are highly effective in reducing drivers’ speed inside work zones. The practical outcome of this effort described in this paper is the Work Zone Police Enforcement Programming Tool (PEPT) used by INDOT to program cost-effective police enforcement activities.
1 INTRODUCTION

Traffic safety is among the highest priority goals of U.S. highway agencies. In the particular area of traffic safety in work zones, the objectives of officials are to better protect construction workers often exposed to high speed traffic and to prevent crashes involving road users passing through work zones. This attention by transportation agencies and researchers is justified because there is a higher frequency of crashes in work zones than for other road segments operating under similar traffic volumes. This situation is further amplified by the aging U.S. highway system which is in need of reconstruction and rehabilitation projects at an ever increasing rate. The particular attributes of work zones that raise traffic safety concerns include:

- modified and usually restrained cross-sections,
- distractions caused by construction activities, and
- changes in road alignment.

The increased variance in driving speeds and added dangerous interactions between vehicles add to the safety concerns.

Federal and state agencies have made continuous efforts to improve safety in highway work zones over the years. The design of modern work zones incorporates safety concerns; strict traffic rules have been established for work zones; and various awareness campaigns aim to improve work zone safety (Tarko et al., 2011). In addition to these efforts, police enforcement in work zones is utilized by many state departments of transportation (DOTs) (Schrock et al., 2002).

The Indiana Department of Transportation (INDOT) has established a special police enforcement program with a dedicated budget for speed enforcement by Indiana State Police (ISP) officers in selected highway work zones. To ensure cost-effectiveness of police enforcement, two conditions need to be met: (1) implement enforcement in work zones with the highest safety benefit potential, and (2) employ enforcement strategies that best fit the work zone conditions. Currently, INDOT uses an expert knowledge-based method that assigns scores to different work zone and traffic features (geometry, traffic volume, crash history, etc.) to identify candidate work zones most promising for police enforcement.

The study presented here was aimed to develop a method that would improve programming of police enforcement in work zones by more cost-effective use of enforcement resources. The developed method includes four components leading to prediction and maximization of the safety benefit in work zones: 1) prediction of the frequency of work zone crashes, 2) estimation of the effectiveness of the most promising police enforcement strategies in reducing speeds in work zones, 3) application of the power model to convert the speed reduction to the corresponding crash reduction, and 4) programming the police enforcement to maximize the safety benefit under the budget and other constraints.

This paper provides a brief description of the first and second components already published elsewhere while a more detailed description of the third and fourth components is provided. The paper is organized as follows. Section 2 provides a literature review; Section 3 briefly reviews the work zone crash frequency model; Section 4 introduces the police enforcement experiment.
and data analysis; Section 5 describes how speed reduction is linked with crash savings; Section 6 introduces the police enforcement programming tool that was developed in the presented study; and Section 7 summarizes the study.

2 LITERATURE REVIEW

The literature review is organized in three parts, corresponding to the three components of the proposed method: prediction of the frequency of work zone crashes, estimation of the effectiveness of police enforcement in work zones, and the power model.

Highway work zones have been found by a number of authors to experience higher crash rates than the same road segments operating under normal conditions. Ha and Nemeth (Ha and Nemeth, 1995) reviewed the literature concerning crash rates in work zones in 1995 and found the crash increase widely varied, ranging from 6.8% to 119%. Later studies confirmed the strongly diverse effect of construction activities. For example, a study (Rouphail et al., 1988) reported crash increases of 69% in long-term work zones and 88% in short-term work zones in the Chicago area. A study in Indiana (Pal and Sinha, 1996) reported a 37.2% increase in all crashes and 66.1% in severe crashes in Indiana. Another study (Khattack et al., 2002) reported a 23.8% increase in non-injury crashes and a 17.4% increase in injury crashes. On the other hand, Jin et al. (Jin et al., 2008) found that the crash rates before and during construction periods did not differ significantly in the studied work zones.

Another direction of past safety research aimed to identify and estimate the various safety factors of highway work zones to find effective countermeasures. A higher ADT, longer work duration, and a shorter work zone length were found to increase both injury and property damage only (PDO) crash frequency (Khattack et al., 2002). Another study in Indiana (Venugopal and Tarko, 2000) found that work zones with high traffic volumes, long segments, and long construction periods experienced lower crash rates (although still higher frequencies) than other work zones. They also found that the intense work activities and lane closures increased the frequency of work zone crashes. Garber and Zhao (Garber and Zhao, 2002) studied crash types and different sections of work zones and found that a rear-end crash was the predominant type for all sections in work zones, with sideswipes second in transition sections and hit-fixed-object crashes second in the actual construction work area. Cheng et al. (Cheng et al., 2012) reviewed work zone crashes in Wisconsin with regard to lane closure features.

Drivers’ choice of speed on highways also has received frequent attention. Tarko (Tarko, 2009) reviewed two schools of thoughts for speed choice (workload-based and risk-perception-based) and concluded that the latter is more widely recognized. Tarko proposed a speed selection model based on a subjective benefit-cost trade-off, in which the perception of the risk of receiving a fine for speeding is among the considered components. He identified a number of factors of speed and concluded that truck drivers are more responsive to speed limits than car drivers.

The effectiveness of police enforcement has long been studied, especially in work zones. Zaal’s review (Zaal, 1994) provided excellent general guidance on the effectiveness of enforcement. While in work zones, the effectiveness of the same enforcement was found to vary considerably across locations (Ullman et al., 2006; Richards et al., 1985), only a few studies
employed a systematically-designed experiment for comparison. Richards et al. (Richards et al., 1985) conducted a “quasi-controlled” experiment, in which several enforcement and non-enforcement strategies were evaluated in several types of work zones. Though his design was not strictly factorial, this study is to date the most systematically designed experiment that evaluated the effectiveness of different strategies. Although a study in Kansas (Bai et al., 2010) used an experiment to compare three non-enforcement strategies, including Variable Message Signs (VMS), the data collection activities were rather intrusive and might have affected the results. Many studies carried out in Illinois extensively studied speed control strategies both with and without police enforcement (Avreni et al., 2012; Benekohal et al., 1992; Medina et al., 2009; Hajbabaie et al., 2011). Different strategies were applied at various locations; thus, separating the enforcement effects from other effects was challenging. Caution is therefore needed when interpreting the results. Both the spatial and temporal “residual” effects of enforcement were found to be short lived by several studies (Tarko et al., 2011; Benekohal et al., 1992; Medina et al., 2009; Hajbabaie et al., 2011; Bloch, 1998; Wasson et al., 2011), which leads to questions about the time, number, and position of enforcement units that are needed in a work zone for a cost-effective enforcement.

Automated enforcement (photo speed enforcement, red-light running cameras, etc.) were pointed out as a promising direction for traffic law enforcement due to its effectiveness and relatively low costs (Zaal, 1994). These strategies have been found effective in work zone speed enforcement in several U.S. studies (Bloch, 1998; Medina et al., 2009). Unfortunately, the current Indiana law does not allow using photo-enforcement techniques. Although automated enforcement was not included in the scope of the presented study, it should be considered in other jurisdictions.

In the current literature, the predominant measure of police enforcement effectiveness has been speed reduction with some consideration given to the speed variance. Because there is no research that directly links police enforcement with crash frequency and severity, a so-called “power model”, a well-documented relationship between the speed and crash reductions (Elvik, 2009), was proposed to predict safety benefits generated by police enforcement. The power model was calibrated by Elvik via a meta-analysis on a large number of studies relating speed reduction with crash reduction. Although work zone conditions were not specifically considered in the meta-analysis, the updated version of the power model made a distinction between high-speed and low-speed facilities (Elvik, 2009).

3 PREDICTING WORK ZONE CRASHES

Good prediction of the monthly number of crashes requires specific work zone information. Such information has not been readily available. A study in Wisconsin (Cheng et al., 2012) linked the crash database with the “Wisconsin Lane Closure System” to gain more insight about the work zone; the National Corporative Highway Research Program (NCHRP) 627 (Ullman et al., 2008) utilized the Work Zone Accidents Database from NYSDOT, which has very detailed information regarding work zone crashes. Yet, neither data source provided enough detailed information about all work zones.
To fill this gap in the data, a survey of project engineers was designed and conducted. Distinct construction phases with start and end dates, the cross-section design during the work zone period, the traffic management components, and the basic information regarding each work zone were collected from project engineers responsible for recent work zones across Indiana.

In addition to the geometry data, temporal data such as traffic variation, monthly indicators, and work zone feature changes were collected to check their effect on the crash frequency. The final sample was designed with monthly observations to allow accounting for the temporal variations of certain work zone conditions.

The final dataset included 70 work zones (547 monthly observations with 1,757 crashes). Random Effect Negative Binomial models were selected to account for both the potential over-dispersion and the shared unobserved correlations due to the monthly observations repeated at the same work zones (Washington et al., 2010). Several work zone features (lane shift, lane split, and both high and low construction intensity) were found to significantly increase crash frequency. The construction intensity was defined as “high” if the monthly-average construction expenditure was higher than $35,000 per day per mile, and defined as “low” if the monthly-average construction expenditure was lower than $10,000 per day per mile. According to the results, the summer and winter months both experienced more crashes than other months. Other roadway related variables, like the indicator for urban and full access control, narrower left shoulder or right of way width, all are associated with a higher crash frequency.

More details about the development of this model can be found in (Chen and Tarko, 2012).

4 WORK ZONE POLICE ENFORCEMENT EXPERIMENT

The second major research component in this study was to evaluate the effectiveness of various enforcement strategies in highway work zones. As mentioned in the literature review, only a few past studies compared selected enforcement strategies in highway work zones in a systematic manner, thus knowledge about the effectiveness of police enforcement useful for our research purpose was insufficient. Furthermore, emerging new enforcement strategies called for conducting of well-designed new studies.

Due to the limited resources available for this study, the authors carefully determined the scope of data collection and utilized four well-established findings from past literature:

1. The same strategy may have different effectiveness in different work zone conditions;
2. Stationary police enforcement is most effective and consistent;
3. Both temporal and spatial residual effect of police enforcement is negligible; and
4. Raising the motorists’ awareness of police presence in the work zone is highly effective.

The third assumption requires clarification. Several studies, including the one presented here, indicated a quick rebound of speed to its original value shortly after the police enforcement ends or at a short distance downstream of the enforcement site. This result applies to the most effective highly conspicuous enforcement strategies. This strategy makes sense if the enforcement must be highly effective at certain times and locations, like work zones. Another approach to enforcement is needed if the objective is to improve the behavior of drivers in large
areas and for a long run (Zaal, 1994). In such cases, the enforcement should be rather inconspicuous, random in space and time, and applied persistently.

With the above four assumptions, the authors designed a factorial experiment with blocking (Montgomery, 2008). Two treatment factors were used: intensity of stationary police enforcement vehicles (PEV) and use of Variable Message Sign (VMS). Work zone segments were used as blocks to keep the dimension of this experiment in check. In this way, four different combinations of treatment factors (along with no enforcement for comparison) were repeated for two days at each work zone. The order of the treatments were flipped the second day to counterbalance the time-of-day effect.

The details of data collection, processing, and analysis can be found in (Chen and Tarko, 2013). A speed-selection multilevel model was estimated to allow the intra-level and inter-level interactions and to account for the shared unobserved heterogeneity (Single and Willette, 2003). The estimated effectiveness is presented in Table 1.

Table 1: Normal Speed and Effectiveness of Enforcement in Work Zones

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>No Enforcement</th>
<th>PEV(^1) at Beginning</th>
<th>PEV Inside</th>
<th>PEV at End</th>
<th>PEV Upstream</th>
<th>VMS01(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Lane Freeway Work Zone without System Interchange (Category 1, 45 mph speed limit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cars</td>
<td>57.21</td>
<td>-3.28</td>
<td>-2.47</td>
<td>N/S(^4)</td>
<td>-1.97</td>
<td>-3.61</td>
</tr>
<tr>
<td>SU(^3)</td>
<td>54.54</td>
<td>-3.28</td>
<td>-2.47</td>
<td>N/S</td>
<td>-1.97</td>
<td>-2.68</td>
</tr>
<tr>
<td>Truck trailer</td>
<td>54.54</td>
<td>-2.45</td>
<td>-3.61</td>
<td>N/S</td>
<td>-1.97</td>
<td>-2.68</td>
</tr>
<tr>
<td>Multi-Lane Freeway Work Zone with System Interchange (Category 2, 45 mph speed limit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cars</td>
<td>45.37</td>
<td>-0.73</td>
<td>N/A(^5)</td>
<td>N/S</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SU</td>
<td>43.19</td>
<td>-0.73</td>
<td>N/A</td>
<td>N/S</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Truck trailer</td>
<td>43.19</td>
<td>-0.73</td>
<td>N/A</td>
<td>N/S</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Non-Freeway Work Zone (Category 3, 35 mph speed limit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cars</td>
<td>40.97</td>
<td>-2.04</td>
<td>-2.04</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>SU</td>
<td>38.21</td>
<td>-0.95</td>
<td>-0.95</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Truck trailer</td>
<td>39.36</td>
<td>-2.04</td>
<td>-0.30</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Single-Lane Freeway Work Zone without System Interchange (Category 4, 45 mph speed limit)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cars</td>
<td>44.83</td>
<td>-2.20</td>
<td>N/S</td>
<td>N/S</td>
<td>N/S</td>
<td>-3.57</td>
</tr>
<tr>
<td>SU</td>
<td>44.83</td>
<td>-2.20</td>
<td>N/S</td>
<td>N/S</td>
<td>N/S</td>
<td>-3.57</td>
</tr>
<tr>
<td>Truck trailer</td>
<td>44.83</td>
<td>-2.20</td>
<td>N/S</td>
<td>N/S</td>
<td>N/S</td>
<td>-3.57</td>
</tr>
</tbody>
</table>

\(^1\)PEV denotes Police Enforcement Vehicle, \(^2\)VMS01 denotes a Variable Message Sign within one mile upstream of segment, \(^3\)SU denoted single unit truck, \(^4\)N/S denotes variable not significant in the model, \(^5\)N/A denotes strategy not available from experiment

The findings regarding work zone police enforcement and its effectiveness from both the field observations of the speed reductions and the model estimation can be summarized as follows. A VMS unit displaying a warning about the ongoing enforcement was found to be remarkably
The model indicated that the speed rebounded rather quickly downstream of the position of the enforcement unit, as shown by the diminished effect from an upstream location. This finding provided a basis for choosing a sufficient but not excessive number of enforcement units for a work zone. The speeds varied significantly across various work zones both with and without enforcement. The significant random effects at both the vehicle group and work zone segment levels confirmed the previous findings that there are many unknown local effects that significantly affect drivers’ speed selection.

The work zone police enforcement study component confirmed that stationary police enforcement and VMS are effective in highway work zones. This effectiveness, measured with the reduction in the average speed through segment, depended on the number of enforcement units, their positions in relation to the work zone, and other characteristics of the work zone.

Although the effect of police enforcement was measured with the speed reduction, the later estimated speed-based safety effect of the enforcement included other behavioral changes caused by police enforcement, such as an increase in driver tentativeness, paying more attention to the road and traffic, and less frequent lane-changing to pass other vehicles (in multiple-lane zones).

## 5 CALCULATING COST AND BENEFIT OF POLICE ENFORCEMENT

Benefit-cost analysis is an essential element of decision-making in U.S. transportation agencies. Estimating the cost of police enforcement is straightforward. Because Indiana State Police officers are paid at a fixed hourly rate, the total cost estimation of enforcement is the product of the hourly rate and the total enforcement hours.

The benefit, on the other hand, is the monetary value of the crashes (at various injury levels) saved by the introduction of police enforcement. The estimation of such benefit involves several steps. First, the expected number of crashes at two levels of severity (fatal/injuries, property damage only) are predicted assuming no enforcement. Second, the numbers of crashes saved due to the enforcement are calculated by applying the Crash Modification Factors (CMFs). Finally, the costs of crashes, which vary considerably with the severity of injuries, are estimated for different severity levels and then summed up. The police enforcement takes places only during certain hours and no effect is assumed during other hours, thus the safety benefit of enforcement must be estimated only for the time when enforcement is present.

The prediction of crashes at two levels of crash is done by applying the crash model presented in Section 3 to estimate the monthly number of crashes \( C_{\text{Tot}} \). Then, these crashes are adjusted with Equations 1 and 2. The adjustments used in Equations 1 and 2 are shown in Table 2, which is calculated using crash data in the work zones and verified against those for the entire state of Indiana.

\[
\begin{align*}
C_{\text{PDO}} &= C_{\text{Tot}} \times P_{\text{PDO}} \times P_{\text{Weekday}} \times P_{\text{Day}} \\
C_{\text{Injury}} &= C_{\text{Tot}} \times P_{\text{Injury}} \times P_{\text{Weekday}} \times P_{\text{Day}}
\end{align*}
\]
Table 2: Proportions of Crashes

<table>
<thead>
<tr>
<th>Road Classification</th>
<th>P_{Weekday}</th>
<th>P_{Day}</th>
<th>P_{Injury}</th>
<th>P_{PDO}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban Freeway</td>
<td>0.7826</td>
<td>0.6124</td>
<td>0.1759</td>
<td>0.8241</td>
</tr>
<tr>
<td>Urban Non-Freeway</td>
<td>0.7750</td>
<td>0.6486</td>
<td>0.2037</td>
<td>0.7963</td>
</tr>
<tr>
<td>Rural Freeway</td>
<td>0.7173</td>
<td>0.4574</td>
<td>0.1570</td>
<td>0.8430</td>
</tr>
<tr>
<td>Rural Non-Freeway</td>
<td>0.7412</td>
<td>0.5894</td>
<td>0.2481</td>
<td>0.7519</td>
</tr>
</tbody>
</table>

The numbers of PDO and injury/fatal crashes calculated with Equations 1 and 2 are predictions for the period of the planned enforcement (weekday between 8 am and 6 pm) if the enforcement did not happen. CMFs are needed to estimate the number of crashes when the enforcement is applied and the difference between the two predictions is the number of crashes saved due to the enforcement. The power model (Elvik, 2009) shown in Equation 3 is used to calculate the CMFs:

\[
CMF = \frac{\text{Crashes during Enforcement}}{\text{Crashes without Enforcement}} = \left( \frac{\text{Speed during Enforcement}}{\text{Speed without Enforcement}} \right)^{\text{Exponent}}
\]

Although the recently published power model provides separate exponents for four injury levels (the most commonly used KABCO injury scale has five levels), due to the small sample size, the authors decided to use two categories: PDO crashes, and injury/fatal crashes with the exponents of 1.5 for PDO crashes and 1.6 for injury/fatal crashes. Since speed and effectiveness of enforcement differ across vehicle classes and work zone categories, the calculations for CMFs were also done accordingly. Example CMFs are shown in Table 3, where the EFC-1 indicates one police enforcement unit at its most effective location – the beginning of the work zone, EFC-2 and EFC-3 add second and third units at the second and third most effective locations. However, the CMFs for EFC-2 and EFC-3 should only be applied when the work zones are long enough and can safely accommodate police units inside the work zone. This table clearly indicates the effectiveness added by VMS.

Table 3: Crash Modification Factors for Enforcement (on Normal Freeway Work Zones)

<table>
<thead>
<tr>
<th>Veh-Type</th>
<th>Injury Crash Modification Factor</th>
<th>PDO Crash Modification Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No VMS</td>
<td>With VMS</td>
</tr>
<tr>
<td>EFC-1</td>
<td>0.910</td>
<td>0.844</td>
</tr>
<tr>
<td>EFC-2</td>
<td>0.780</td>
<td>0.708</td>
</tr>
<tr>
<td>EFC-3</td>
<td>0.814</td>
<td>0.751</td>
</tr>
<tr>
<td>EFC-1</td>
<td>0.690</td>
<td>0.663</td>
</tr>
<tr>
<td>EFC-2</td>
<td>0.707</td>
<td>0.707</td>
</tr>
</tbody>
</table>

The next step is to convert the saved crashes into an equivalent safety benefit expressed in monetary value. The Center for Road Safety at Purdue University prepares every year for the Indiana Department of Transportation (INDOT) a Five-percent Report, which identifies high-
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Crash locations in Indiana and provides the average crash costs for each injury category. Although no special considerations were given to work zones in this report, neither does the cost figures published by NHTSA (Blinco, et al., 2000) or NSC (National Safety Council, 2011). Considering the locality (all data in this study coming from Indiana) and the timeliness (the 2011 version used crash data from 2008 to 2010), the cost figures from the Indiana 2011 Five-percent Report (Brown et al., 2011) were chosen over those by NHTSA or NSC. The cost figures are shown in Table 4.

Table 4: Cost Figures from Indiana 2011 Five-Percent Report

<table>
<thead>
<tr>
<th>Injury Level</th>
<th>Injury PDO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Crash Cost For Entire Indiana</td>
<td>65,708.36 6,507.70</td>
</tr>
</tbody>
</table>

Applying the cost figures to the numbers of crashes saved, the total monetary benefit of the police enforcement could be calculated for each enforcement strategy.

6 ENFORCEMENT PROGRAMMING TOOL

The final component of this study is the development of the Police Enforcement Programming Tool (PEPT). As the findings from this study will be implemented by INDOT, all the research findings were implemented through a convenient computer application in a Microsoft Excel environment. The developed programming tool includes four modules: input, pre-calculation, optimization, and results.

The first module is a data input module. The general programming scope and detailed work zone information were required for such programming and includes the programming period, total budget, the number of available ISP officers and VMS units, and the enforcement cost rate. The programming period enables the flexibility of programming for either an entire fiscal year or detailed programming for certain months or even one month. The number of available VMS units can be specified by the INDOT district and the number of available police officers by the ISP post. The work zone input includes the variables needed to predict the number of crashes without enforcement and the speeds without and with enforcement. These input values allow calculating the crash savings for each police enforcement strategy applicable to the work zone. Also included in this module are “user enforcement decision variables.” These inputs allow the users specifying the work zones to be enforced regardless of the cost-effectiveness. Error checking is incorporated to make sure that all input values are reasonable.

The second module is the pre-calculation module. This module incorporates the results from the research components described in Sections 3 through 5. The benefits and costs of relevant enforcement strategies are calculated for each candidate work zone and for each month during the construction period. These calculations are performed automatically if all the required inputs are properly entered.

The third module is the optimizer. The optimization program uses integer programming with binary decision variables for each work zone, each month, and each strategy. This integer
optimization seeks to maximize the benefit of enforcement, and subject to a series of real world constraints, including the “user enforcement decision” special feature. The objective function and all constraints are shown in Equation (4) though Equation (9).

\[
\text{Max } \sum_{i \in I} \sum_{k \in K} X_{ik} (B_{ik} - CV_{ik})
\]

subject to the following constraints:

Maximum budget,

\[
\sum_{i \in I} \sum_{k \in K} X_{ik} C_{ik} \leq \text{Budget}
\]

Maximum number of police units (one constraint per ISP post) at post j and during period t,

\[
\sum_{i \in I_j} \sum_{k \in K} X_{ik} PU_{ik} \leq \text{Max PU}_{jt}
\]

Maximum number of VMS units (one constraint per INDOT district) in district j and during period t,

\[
\sum_{i \in I_j} \sum_{k \in K} X_{ik} VMS_{ik} \leq \text{Max VMS}_{jt}
\]

One strategy constraint per work zone (no multiple strategies in the same work zone and at the same time),

\[
\sum_{k \in K} X_{ik} \leq 1
\]

User-required enforcement for user-selected work zones,

\[
\sum_{k \in K} X_{ik} = 1 \text{ (when "Yes") or } 0 \text{ (when "No")}
\]

where X is the decision variable, B is the benefit from enforcement, CV is the cost for VMS (as the cost for VMS does not incur to the enforcement fund), PU is the number of police units, VMS is the number of VMS used. Subscript i denotes work zone, subscript k denotes enforcement strategy, subscript j denotes area, and subscript t denotes time interval.

The above problem exceeds the capability of the standard Microsoft Excel Solver and we resorted to OpenSolver (Mason, 2012), a public-domain Excel macro developed to handle large multi-dimensional optimization problems. The maximum problem size was set in the optimizer to 300 work zones, and the running time during the test was approximately seven minutes, which is acceptable.
The final module in this programming tool is the results presentation module, which includes the decision matrix and the detailed benefit/cost information. In the decision matrix, the optimized enforcement strategies are presented for each work zone and each month. At the end of the matrix, the overall estimated benefit and cost, along with the benefit/cost ratio, are produced, thereby providing the user information about the overall cost effectiveness. In the detailed information section, the estimated crash frequency, the CMFs (injury/PDO), and the enforcement benefits and costs are provided for each work zone/enforcement strategy combination.

The users can vary the “user enforcement decision variables” to override the optimizer in order to accommodate special enforcement needs. The effect of such user interventions can be evaluated with the benefit/cost ratio.

7 CONCLUSION
The four-step method for optimizing police enforcement program in Indiana work zones was presented in this paper. With relatively minor modifications, this method is applicable to other regions.

In the first phase of the research study, the frequency of crashes inside a work zone was analyzed with an extensive work zone crash database. Several work zone features were identified to be associated with the frequency of crashes, with some not found in the past literature (e.g. low construction intensity). It would be extremely helpful for future efforts on studying the safety factors and improving in work zones of work zone safety if road administration maintains a good quality work zone database.

In the second phase of the research, the speed and other data were collected in work zones that underwent carefully designed police enforcement experiments. A hierarchical model of speed was estimated with the collected data. The results provided strong statistical evidence of several generally accepted facts about police enforcement including the effectiveness of stationary police enforcement, the quickly elapsed spatial residual effect, and the significance of local conditions sometimes neglected in the past studies. The results also revealed new facts such as the high effectiveness of VMS units, and the varying effectiveness of police enforcement in reducing speed of different types of vehicles and in different work zone categories.

The final outcome of the research is the Police Enforcement Programming Tool (PEPT), which utilizes the developed crash and speed models. The PEPT is used by INDOT to program future police enforcement in Indiana work zones.

DISCLAIMER
The contents of this paper reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Indiana Department of Transportation, the Indiana State Police or the Federal Highway Administration at the time of publication. This paper does not constitute a standard, specification, or regulation.
REFERENCE


