

EVALUATION OF STRATEGIES TO MANAGE SPEED IN HIGHWAY WORK ZONES

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ABSTRACT

Safety in reconstruction and maintenance work zones continues to be the primary concern of transportation engineers. Speeding is one of the major contributors of work zone crashes. To decrease the occurrence of potential speeding-related crashes, the Wisconsin Department of Transportation (WisDOT) is seeking effective methods of controlling speed at Wisconsin work zones to improve traffic safety.

In an attempt to better understand how the speed control strategies impact work zone speed in Wisconsin, this study was designed to evaluate the performance of several speed control strategies and identify the most effective strategies under specific work zone conditions. Speed control strategies including the use of dynamic speed display board and three enforcement methods were evaluated at Wisconsin long-term highway work zones located on State Trunk Highway (STH) 29 and STH 164, respectively. Compared with previous research, the study provides more insight into the long-term impact of these speed control strategies.

The results show a promising outcome of using these strategies in Wisconsin work zones. Time of day, truck percentage, and free-flow speed affected the performance of speed control strategies in work zones. Further, a new approach was developed based on regression models to compare the effectiveness of speed control strategies under varying traffic conditions, and therefore, to assist engineers in selecting appropriate strategies.

KEY WORDS: Work Zone Safety, Speed Management, Before-and-after Analysis, Regression Analysis

INTRODUCTION

The interstate highway system celebrates its 50th birthday in 2006. Given this duration of service, it is no surprise that reconstruction and maintenance work are needed to provide a safe and comfortable driving environment to road users. Since it is not operationally desirable to fully close roadway segments, work zones present a temporary roadway condition that may violate drivers' expectation and therefore, have the potential to compromise the safety of workers and road users.

Safety in reconstruction and maintenance work zones continues to be the major concern of transportation engineers. Speeding is one of the major contributing factors of work zone crashes. Speeding reduces the driver's ability to safely control, guide, and navigate a vehicle, which increases the possibility of crash occurrence. Many speed control techniques are currently being used throughout the country. To decrease the occurrence of potential speed-related work zone crashes, the Wisconsin Department of Transportation (WisDOT) is seeking effective methods to manage Wisconsin work zone speed. In response, the strategies' effectiveness in reducing work zone average speed and the number of speeders should be evaluated.

Given changeable traffic and work zone conditions, different strategies can impact work zone traffic flow in various ways. Although a significant amount of research has been conducted to evaluate the effectiveness of different traffic control strategies, the results vary widely from one study to another due to varying work zone conditions. Herein, the uniqueness of the work zone configuration makes it always a perplexing problem to determine how each of these strategies performs under a specific work zone condition.

This study is part of a WisDOT program aimed at evaluating advanced work zone management and safety strategies and monitoring work zone speed. There are three primary objectives in this study:

- Record and compare the speed characteristics with and without speed control strategies in work zones;
- Measure the effectiveness of speed control strategies in work zones; and
- Compare the effectiveness of speed control strategies under varying traffic conditions with respect to speed reduction.

The proposed strategies range from conventional approaches to more sophisticated technologies. The evaluation includes two phases, Phase I (2005) and Phase II (2006). This paper describes two types of conventional strategies evaluated in Phase I: dynamic speed display board (DSD) and enforcement. These strategies were applied to two long-term highway work zones on State Trunk Highway (STH) 29 and STH 164 separately.

LITERATURE REVIEW

A number of studies have been conducted to evaluate the effectiveness of DSD and enforcement in work zones. This section gives a brief review of previous research related to this study.

The Texas Transportation Institute organized a two-year project to identify the effectiveness of work zone traffic control technologies (1). DSD was tested on two rural high-speed temporary work zones. The "before" data were collected in the morning and "after" data in the same day afternoon. The results showed that the DSD gained a speed reduction of 2.0 to 7.5 miles per hour (mph) upstream of the work zone and 3.0 to 6.0 mph within the work zone. A study in Virginia by Garber and Patel used Changeable Message Signs (CMS) to warn drivers

when their operating speed exceeded the posted speed limit (2). The results indicated that average speed was reduced by 4.0 mph and 85th percentile speed was reduced by 6.0 mph. In addition to short-term evaluations, Garber measured speed reduction for a seven-week period (3). The speed reduction ranged from 5.0 to 10.0 mph on interstate highways and 8.0 to 12.0 mph on primary roads. Lower speeding percentages and smaller speed variance were reported as well. Pesti and McCoy's study in Nebraska showed a positive novelty impact of DSD on the average speed during the first week, but the effectiveness was weakened in the second week (4).

Most of the speed control strategies achieved the maximum effectiveness in reducing work zone speed in conjunction with enforcement. Enforcement alone is also a common practice of work zone operations in many states. A study conducted in Texas by Richards evaluated the effectiveness of stationary and mobile enforcement at six work zones (5). The study revealed that stationary enforcement reduced the average speed by 4.0 to 12.0 mph at urban sites while mobile enforcement gained 2.0 to 3.0 mph reduction on rural two-lane highways. Schrock conducted a telephone survey for the deployment of enforcement in work zones (6). Based on the interview results, this study indicated that the high cost associated with enforcement was the primary constraint to this method of effectively managing speed in work zones.

These evaluations showed positive results for the selected strategies implemented in work zones. Notice that all the field tests were conducted in varied work zone environments with different work zone configurations, traffic conditions, and roadway geometry. As a result, given the wide range of variation in test fields and results of these previous studies, traffic engineers still confront the problems of selecting appropriate work zone speed management strategies.

TEST SITES AND SPEED CONTROL STRATEGIES

Dynamic Speed Display Board

DSD technology is one of the most commonly used speed control strategies. DSD includes a speed radar sensor to detect the approaching vehicle speed and a changeable display board to show the measured speed. In general, DSD is attached to a portable trailer. Additionally, a regulatory speed limit sign is placed above the display board. By doing this, the drivers can be informed of their speed and the relationship to the posted speed limit. It is assumed that drivers will reduce their speed if the display board shows that their speed exceeds the posted speed limit. Since the majority of previous DSD evaluations were conducted during the initial implementation period when speed reduction may be partially attributed to a novelty effect (1, 2, 4), special interest was given to evaluating the long-term effectiveness of DSD on drivers' speed.

A 0.873 mile long construction zone at which DSD was implemented for two months was selected for evaluation. STH 29 is a four-lane divided highway with two 12-foot lanes in each direction. Partial lane closure was used as the traffic control strategy. The speed limit in the work area was reduced from the posted 65 mph to 55 mph.

Enforcement

Traffic law enforcement by marked and unmarked law enforcement officials is a well recognized effective speed control strategy. The sufficiently validated assumption is that drivers will comply with the posted speed limit when they observe a police vehicle or feel a threat of receiving a speeding citation. Intuitively, more significant enforcement presence can achieve

more benefits in reducing the number of speeders. Unfortunately, the high cost of extra enforcement is commonly a constraint. Given the limited construction management budgets, limited enforcement opportunities need to be efficiently taken to obtain maximum speed management results. Several enforcement strategies were evaluated in this study to determine how effectively they managed work zone speed, including mobile, minimum stationary and intensive stationary methods. Mobile enforcement was defined as moving vehicle enforcement with police officers driving along the work zone area from time to time. Stationary enforcement was classified into minimum and intensive enforcement: minimum stationary enforcement employed one police officer in a parked vehicle location, and intensive stationary enforcement employed two officers at two parked locations within the work zone.

The enforcement and traffic data were collected at a 3.77 mile long work zone on STH 164 in Waukesha County, Wisconsin where the work zone speed limit was reduced from the original 55 mph to 45 mph. Similar to the DSD evaluation, long-term performance was emphasized in this enforcement evaluation.

Data Collection

The University of Wisconsin Traffic Operations and Safety (TOPS) Laboratory used non-intrusive traffic data collection devices, Remote Traffic Microwave Sensors (RTMS), to collect volume and speed data. The sensors were powered by battery with a solar power recharging unit. Data were stored at five-minute intervals in the Remote Traffic Counter (RTC) unit with 4Mb capacity, allowing up to seven-month of continuous data collection if desired. Figure 1 shows a typical RTMS traffic data collection system. Due to the nature of non-intrusive data collection, RTMS can be placed and removed safely without disturbing traffic in the work zone. The quality of RTMS data was calibrated by a hand-held Lidar gun.

To measure the effectiveness of the speed control strategies, both “before” and “after” volume and speed data were collected. “Before” data were collected without speed control strategies while “after” data were collected with strategies in operation. The length of the “before” and “after” data collection periods lasted for at least two weeks, depending on the working schedule of the specific work zone.

In addition, RTMS systems were placed at two locations along the work zone. The first data collection site was approximately one mile upstream of the work zone. This site captured vehicular speed in a free-flow condition. The free-flow speed reflected the traffic under normal conditions without the impact of work zone configurations and the speed control strategies and provided a baseline for data analysis. The second site was directly within the work zone to measure the speed reduction from the free-flow speed.



FIGURE 1 RTMS traffic data collection system.

METHODOLOGIES

Before-and-after Analysis

The purpose of speed control strategies is to manage traffic in work zones. Therefore, a before-and-after analysis was designed to compare the changes in speed measures. The average speed, 85th percentile speed, speed variance, speed distribution, and percentage of exceeding speed limits were designated as the measures of effectiveness (MOEs) in this study. The change in these speed characteristics was defined as the difference between before and after strategy implementation. Note that these commonly used MOEs did not reflect the potential impact of

speed control strategy on various driver groups. To capture the speed reduction of various driver groups, net speed reduction was defined as follows to offset the variability in speed reduction behavior of different driver populations (7, 8):

$$\text{Net speed reduction} = (u_{a2} - u_{b2}) - (u_{a1} - u_{b1}) \quad (1)$$

Where u_{b1} – free-flow speed during before period,

u_{a1} – free-flow speed during after period,

u_{b2} –speed in the work zone during before period, and

u_{a2} –speed in the work zone during after period.

T-tests and Chi-square tests were performed to examine the significance of changes in these speed measures before and after strategy implementation. Specifically, T-test was used to determine whether the change in speed measures was statistically significant and Chi-square test was used to find whether the speed control strategies significantly affected the speed distribution (percentages of vehicles in certain speed ranges) and to determine whether the percentage of speeders decreases significantly.

Regression Analysis

To investigate the relationship between the operating speed in work zones under a certain traffic condition and speed control strategy, a linear regression analysis was conducted using the field obtained data. The general model is expressed as follows:

$$Y = \beta_0 + \beta_1 X_1 + \dots + \beta_n X_n + \gamma_1 X_1 X_2 + \gamma_2 X_1 X_3 + \dots + \gamma_m X_{n-1} X_n \quad (2)$$

Where:

Y – Response (Speed in the work zone)

X – Predictor Variables (speed control strategy, traffic condition variables, etc.)

β , γ – Coefficients

The purpose of the regression analysis was to identify the work zone characteristics and speed control strategies, or their interactions, which affected work zone speed. Further, statistical models were developed to quantify the impact of speed control strategies on speed in work zones under given traffic conditions.

RESULTS

Before-and-after Speed Descriptive Statistics

Data analysis focused initially on the computation of data obtained, followed by the before and after statistical analysis. All statistical procedures were tested at a 95 percent level of confidence. The calculation and analysis were based on binned data stored at five-minute intervals. Moreover, because traffic volume, especially the truck volume, varied throughout the day, daytime and nighttime speed characteristics are presented separately to ensure that the before-and-after comparison is under the similar traffic conditions.

The average speed and standard deviation under each speed control strategy at free-flow section and within the work zone section for the “before” and “after” period are given in Table 1. Free-flow speed characteristics in the “before” period were similar to the “after” period,

indicating a similar traffic condition throughout the data collection. Table 2 summarizes the change in average speed, 85th percentile speed and net speed reduction in work zones under the four speed control strategies.

TABLE 1 Speed Statistics for Free-Flow and Work Zone Segments

Strategy	Time	Free-Flow Speed (mph)				Work Zone Speed (mph)			
		Before		After		Before		After	
		Average	Std. Dev	Average	Std. Dev	Average	Std. Dev	Average	Std. Dev
DSD	Daytime	78.8	5.2	76.0	7.1	51.4	3.5	52.8	3.3
	Nighttime	82.0	5.6	81.3	7.7	54.9	3.2	53.6	3.6
Mobile Enforcement	Daytime	47.4	4.1	47.5	3.2	43.0	4.6	41.6	5.1
	Nighttime	49.2	3.5	49.3	3.2	46.2	3.1	46.0	3.2
Minimum Enforcement	Daytime	47.4	4.3	47.8	3.6	43.0	4.1	42.5	3.8
	Nighttime	49.2	3.5	49.8	2.4	46.2	3.0	46.2	3.0
Intensive Enforcement	Daytime	47.4	4.2	47.4	3.8	43.0	4.3	42.5	5.2
	Nighttime	49.2	3.1	49.2	3.2	46.2	3.4	45.2	3.1

TABLE 2 Before and After Speed Comparison for Four Speed Control Strategies

Strategy**	Time	Speed (mph) Characteristic Change			Percentage of Vehicles in Speed Range		
		Average Speed	85 th ile Speed	Net Speed Reduction	<45	45-55	Over Speed Limit
DSD	Daytime	1.5	1.3	0.3	-4%	-6%	10%
	Nighttime	-1.0*	-0.6	-0.4	2%	12%	-14%
Mobile Enforcement	Daytime	-1.4*	0	-1.5*	6%	-6%	-6%
	Nighttime	-0.2	0	-0.4	5%	-5%	-5%
Minimum Enforcement	Daytime	-0.5	0	-0.9*	3%	-3%	-3%
	Nighttime	-0.1	0	-0.7*	2%	-2%	-2%
Intensive Enforcement	Daytime	-0.6	-1	-0.3	4%	-4%	-4%
	Nighttime	-1.1*	-1	-0.9*	17%	-17%	-17%

* – Statistically significant change

** – The speed limit of the study site for DSD was 55 mph and enforcement site was 45 mph.

Neither a significant reduction in average speed nor reduction in percentage of speeding drivers was observed during daytime hours under DSD. Due to the fact that work activity area was located on the closed lane adjacent to the open lane and drivers can easily observe the presence of workers and construction equipments, the operation speed already decreased even though there was no speed control strategy. Consequently, little room for speed reduction was left after DSD presence and this might account for small change between with or without DSD. This fact also suggests that the long-term placement of DSD board had little impact on daytime speeds. In contrast, the nighttime average speed during the “after” period was 1.0 mph lower when compared with the “before” period.

Although there was a decrease in daytime and nighttime average speed under mobile enforcement, only daytime reduction was statistically significant (p-value < 0.001) and none of them was significant from a practical standpoint. Also, the negative value of net speed reduction demonstrates that mobile enforcement impacted drivers’ behavior and decreased the traveling speed in daytime work zones.

None of the speed reductions were found to be statistically significant under minimum enforcement strategy despite the fact that lower average and median speeds were observed. Nevertheless, the net speed reduction by adjusting for the free-flow speed change was statistically significant. This might suggest that minimum enforcement had a slight impact on nighttime operating speeds in the work zone.

Marginal changes in daytime speed (-0.6 mph) under intensive enforcement can be observed in Table 2; however, the speed change was not statistically significant. The significant speed reduction (p-value < 0.0001) was found in the nighttime when the average nighttime speed reduced from 46.2 mph (“before” period) to 45.2 mph (“after” period). Also, the net speed reduction and 85th percentile speed supported the fact that intensive enforcement impacted nighttime speeds in the work zone.

Although the speed reductions of DSD and intensive enforcement at night and mobile enforcement in daytime hours were found to be statistically significant, the reductions were relatively small from a practical perspective. The small reduction of DSD at the STH 29 work zone may be due to the lack of long-term effectiveness without the support of enforcement. On the other hand, the limited speed reduction with enforcement at the STH 164 work zone may lie in the fact that this work zone location was downstream (free-flow segment) of a 45 mph speed limit zone, the same as the work zone posted speed limit after reducing from original 55 mph. Hence, drivers’ speed was close to the work zone posted speed limit even before entering the work zone and limited speed reduction was needed to obey the work zone speed limit.

Before-and-after Speed Distribution

Figures 2 through 5 illustrate the daytime and nighttime speed distributions under the four speed control strategies. All of these figures demonstrate that the percentage of drivers exceeding the speed limit was higher in the nighttime than the daytime.

Nighttime speed distribution under DSD shown in Figure 2 depicts that the “after” period had fewer drivers speeding during nighttime hours compared with the “before” period, which agrees with the statistical results shown in Table 2 with 14 percent fewer drivers speeding in nighttime hours during the “after” period. The small p-value of less than 0.0001 of nighttime from the Chi-square test showed that DSD impacted the speed distribution during nighttime hours and more drivers reduced operating speeds, which supports the promise of using DSD in work zone speed management.

Although only intensive enforcement led to significant reductions in nighttime travel speeds (p-value < 0.001), speed distribution profiles show that all the enforcement strategies decreased the percentage of drivers exceeding the speed limit to some extent, which agrees with the results in Table 2.

Additionally, it is well documented that the effectiveness of enforcement is related to the police presence on site. However, because the presence of enforcement may not be obvious until drivers observe the police vehicles or flashing lights during a traffic stop or pick up an alarm from their radar detector, drivers may not change operating behavior. To correlate police physical presence and speed reduction, the research team acquired the police work log to collect officer duty time, the number of warnings and citations issued, and the enforcement station positions during the data collection periods. Not surprisingly, intensive stationary enforcement issued the highest number of warnings and citations (78 percent of total warnings and citations).

It is plausible that the more citations are issued, the more reduction in speeding percentage and average speed can be anticipated.

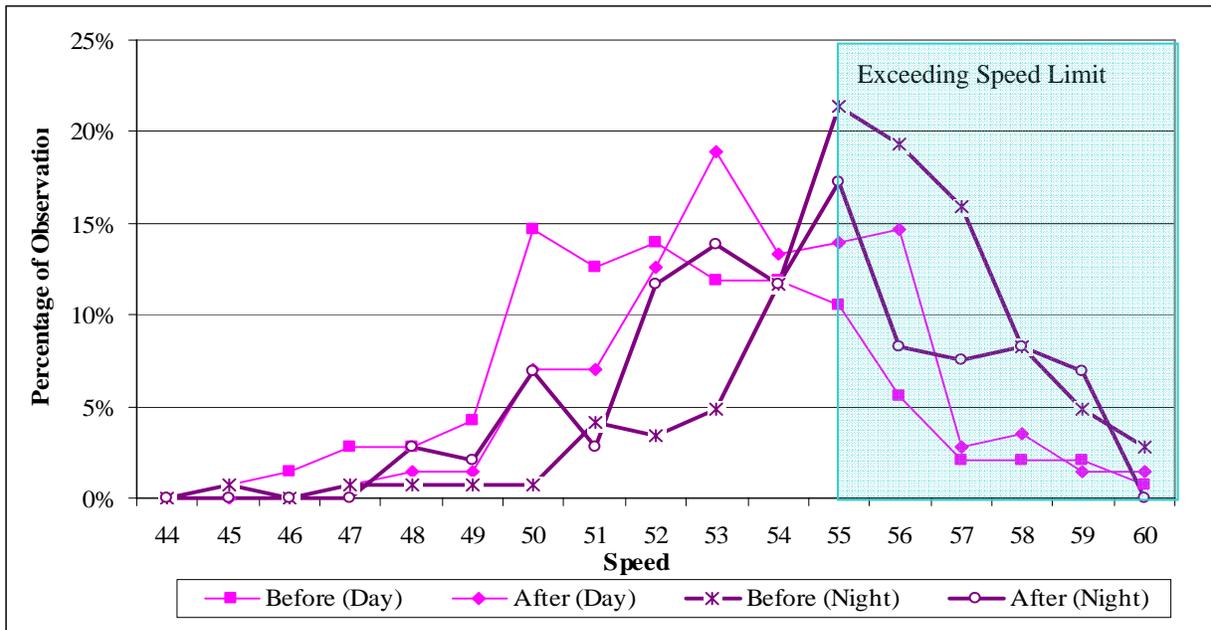


FIGURE 2 Speed distributions for before and after DSD on STH 29.

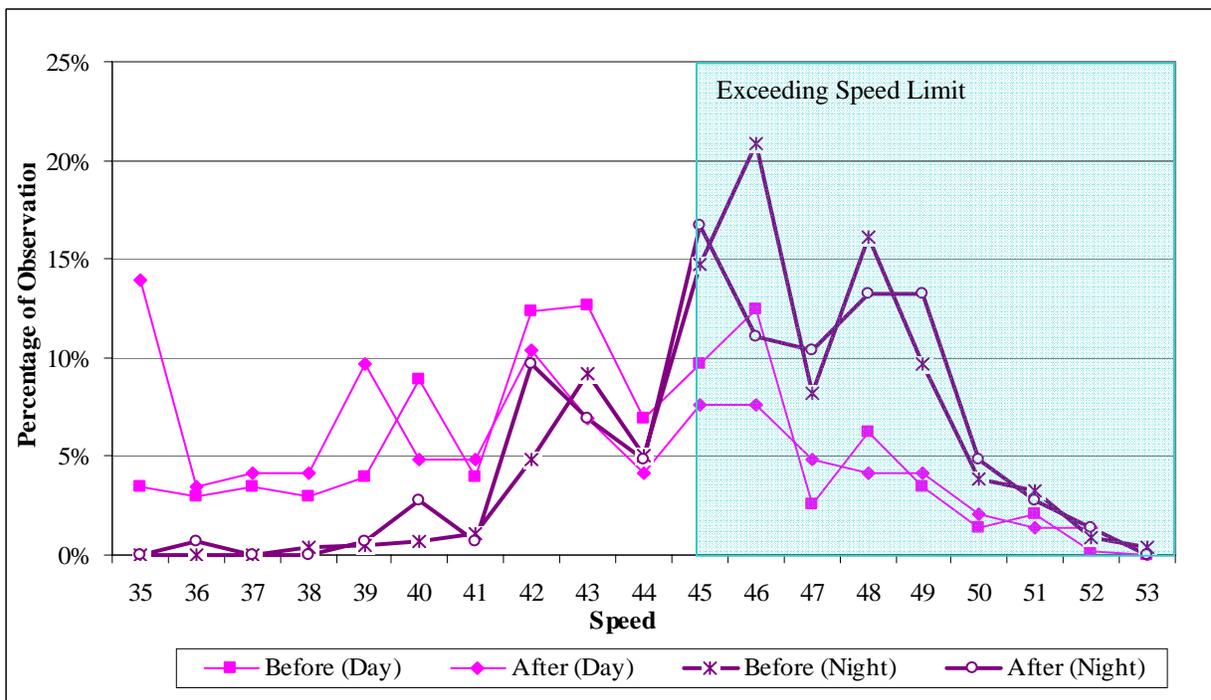


FIGURE 3 Speed distributions for before and after mobile enforcement on STH 164.

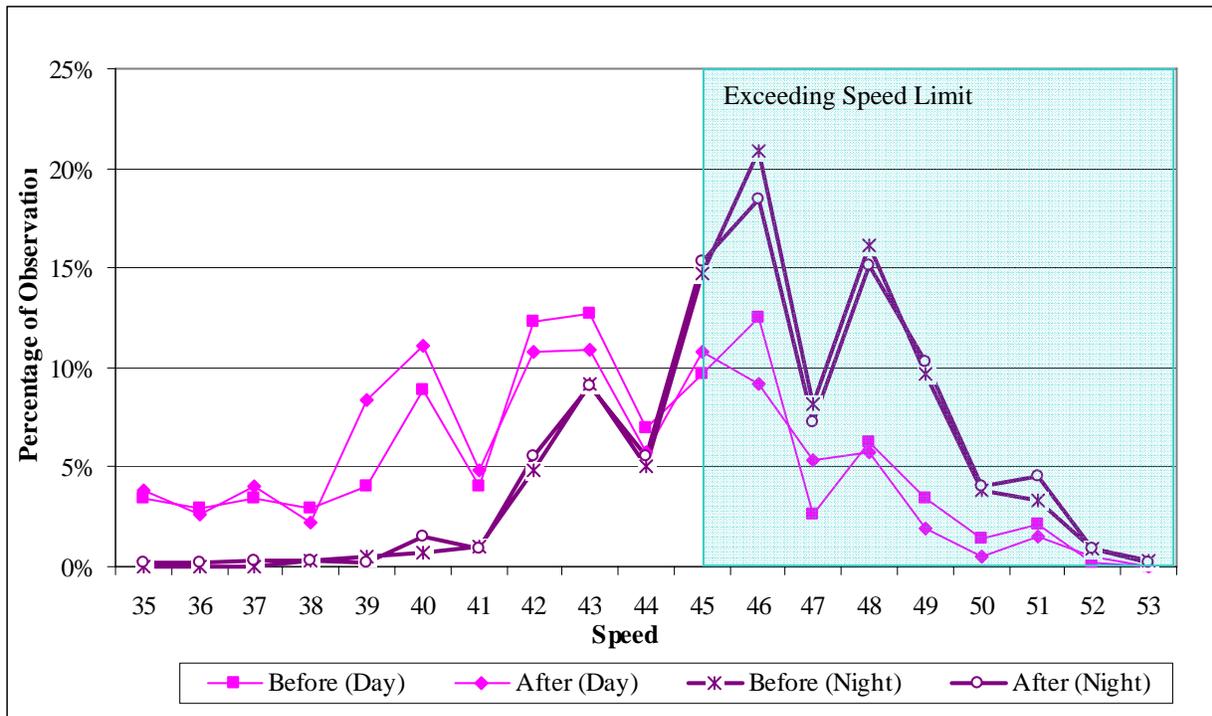


FIGURE 4 Speed distributions for before and after minimum enforcement on STH 164.

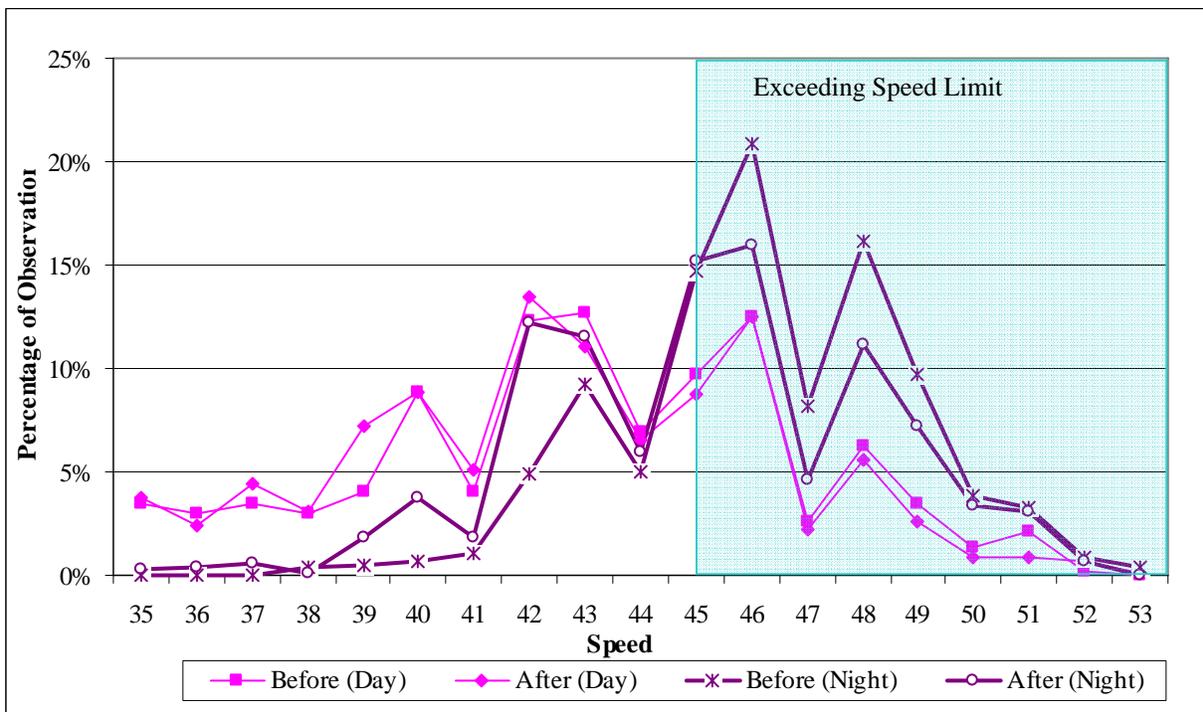


FIGURE 5 Speed distributions for before and after intensive enforcement on STH 164.

Regression Analysis

Preceding analysis shows that the effectiveness of speed control strategies varied from time to time. This fact indicates that speed in work zone was also affected by traveling conditions in addition to speed control strategies. Therefore, a regression analysis was conducted to further investigate the impact of the four strategies under varying traffic conditions. Additionally, the regression analysis was envisioned to be able to assist in selecting speed control strategies. Several variables may influence the operating speed in work zones such as time of day, traffic volume, truck percentage, and free-flow speed in addition to speed control strategy. The brief variable descriptions are illustrated in Table 3.

TABLE 3 Variables in Regression Analysis

	Variable Type	Variable	Description
Response	Continuous	Work Zone Speed	Operating speed in the work zone
			Dynamic Speed Display Board
Predictor	Dummy Variable	Speed Control Strategy	Mobile Enforcement
			Minimum Enforcement
			Intensive Enforcement
	Continuous Variable	Time of Day	Daytime
			Nighttime
Continuous Variable	Continuous Variable	Volume	Number of vehicles
		Truck Percentage	Percentage of truck traffic
		Free-Flow Speed	Operating speed one mile away from the taper

In an attempt to select the best predictor variables for the linear regression model, Akaike Information Criteria (AIC) based on the fitted log-likelihood function was used. The smaller the value of AIC is, the better the model.

$$AIC = -2L(\hat{\beta}) + 2K \quad (3)$$

Where:

$L(\hat{\beta})$ – the log likelihood

K – the number of estimated parameters

The model selection started from a full set of proposed key predictors listed in Table 3 and their two-way interactions. A stepwise procedure combining forward addition and backward elimination was applied to select the best regression model with minimum AIC value using R statistical software (9).

Regression results are presented in Table 4, including the estimates of coefficient, standard error, t-statistic, and p-value. The predictors for work zone speed with p-value less than 0.05 include time of day, truck percentage, free-flow speed, speed control strategy, and the interactions between these variables. In other words, time of day, truck percent, and free-flow speed as well as their interaction effects with speed control strategies influenced work zone speed. For example, the statistically significant coefficient of interaction between time of day and strategies suggests that speed control strategies performed differently in the nighttime compared with daytime. Similarly, free-flow speed and truck percentage also interacted with speed control strategies and influenced their performance. In summary, the significance of

coefficients for interaction effects between strategies and traffic condition variables reinforces that strategies performed differently under varied traffic conditions.

Among these predictors, the constant and main effects in Table 4 reflect the impact of individual variables on work zone speed. The main effects constitute the baselines for speed in work zones under the four strategies. The interaction effects represent the confounded impacts of strategies and traffic conditions on work zone speed. The negative coefficient of each interaction effect indicates that the interaction can lead to the reduction of speed in work zones compared to the baselines with main effects only. In contrast, a positive coefficient suggests an increase from the baselines. All strategies involve both negative and positive impacts confounded by traffic condition variables. This fact raises the question of how to interpret the mixed results. In answer to the question, the speed prediction model for each strategy was developed to help better understand the strategy performance.

TABLE 4 Linear Regression Model Results

Variable	Estimate	Std. Error	t value	Pr(> t)
Constant	29.154	0.803	36.327	0.000*
Main Effect				
Time of Day **	3.769	0.604	6.237	0.000*
Truck Percentage	6.791	2.996	2.267	0.024*
Free-Flow Speed	0.280	0.010	28.428	0.000*
DSD	13.474	2.609	5.165	0.000*
Mobile Enforcement	1.616	3.015	0.536	0.592
Minimum Enforcement	11.470	2.456	4.670	0.000*
Intensive Enforcement	10.021	2.844	3.524	0.000*
Interaction Effect				
Time of Day × DSD	-2.024	0.559	-3.621	0.000*
Time of Day × Mobile Enforcement	1.158	0.557	2.080	0.038*
Time of Day × Minimum Enforcement	-0.188	0.566	-0.332	0.740
Time of Day × Intensive Enforcement	-1.662	0.539	-3.085	0.002*
Truck Percentage × DSD	-0.983	1.289	-0.763	0.445
Truck Percentage × Mobile Enforcement	-12.192	4.614	-2.642	0.008*
Truck Percentage × Minimum Enforcement	-7.187	4.505	-1.595	0.111
Truck Percentage × Intensive Enforcement	2.668	3.060	0.872	0.383
Free-Flow Speed × DSD	-0.148	0.034	-4.320	0.000*
Free-Flow Speed × Mobile Enforcement	-0.053	0.062	-0.848	0.396
Free-Flow Speed × Minimum Enforcement	-0.223	0.051	-4.363	0.000*
Free-Flow Speed × Intensive Enforcement	-0.193	0.058	-3.321	0.001*
Time of Day × Volume	-0.005	0.001	-4.306	0.000*
Time of Day × Truck Percent	-6.056	2.792	-2.169	0.030*
Volume × Truck Percent	-0.026	0.009	-3.025	0.003*

* Statistically significant coefficient

** Time of Day: 0 – Daytime, 1- Nighttime

Residuals: Std. Error = 3.54

Fit: Multiple R-Squared = 0.6478, Adjusted R-squared = 0.643

Model Test: F-statistic [23, 1704] = 136.3, p-value: < 2.2e-16

The models for predicting speed under each speed control strategy in daytime and nighttime are shown in Table 5. By combining the main effects and interaction effects associated with traffic condition variables (free-flow speed, etc.) and speed control strategies, these models are able to explain the impacts of strategies on speed in work zones under a given traffic condition.

The negative coefficient of the traffic volume variable and the positive coefficient of the free-flow variable shown in Table 5 indicate that the free-flow speed always has a positive impact on the work zone speed and the volume always has a negative impact under every strategy. In other words, a high volume and low free-flow speed are expected to generate low work zone speed, which is reasonable. The effect of truck percentage was investigated by changing truck percentage when keeping the free-flow speed and volume constant. Figure 6 represents the work zone speed change trends in daytime and nighttime when the truck percentage ranged from zero to 30 percent. Hourly traffic volume was assumed to be 500 vehicles per hour (vph) and the free-flow speed was 70 mph. The figure indicates that the higher the percent of trucks, the lower the work zone speed will be under each of the four strategy scenarios. Additionally, nighttime speed reduction (line slope in Figure 6) is steeper than that of the daytime, which suggests that nighttime speed in work zone is more sensitive to truck percentage. The same procedure was repeated to examine the effect of truck percentage under scenarios with different values of traffic volume from 300 vph to 2000 vph and free-flow speed from 50 mph to 70 mph. Similar speed patterns as Figure 6 can be observed. Hence, it can be concluded that the truck percentage has a negative impact on work zone speed under each strategy.

TABLE 5 Work Zone Speed Prediction Models for Speed Control Strategies

Strategy	Time of Day	Work Zone Speed Prediction Model*
DSD	Daytime	$42.628 + 0.132 \times S_f + 6.791 \times P_{tr} - 0.027 \times V \times P_{tr}$
	Nighttime	$44.373 + 0.132 \times S_f + 0.735 \times P_{tr} - 0.006 \times V - 0.027 \times V \times P_{tr}$
Mobile Enforcement	Daytime	$29.154 + 0.280 \times S_f - 5.401 \times P_{tr} - 0.027 \times V \times P_{tr}$
	Nighttime	$34.081 + 0.280 \times S_f - 12.006 \times P_{tr} - 0.006 \times V - 0.027 \times V \times P_{tr}$
Minimum Enforcement	Daytime	$40.624 + 0.057 \times S_f + 6.791 \times P_{tr} - 0.027 \times V \times P_{tr}$
	Nighttime	$44.393 + 0.057 \times S_f + 0.735 \times P_{tr} - 0.006 \times V - 0.027 \times V \times P_{tr}$
Intensive Enforcement	Daytime	$39.175 + 0.087 \times S_f + 6.791 \times P_{tr} - 0.027 \times V \times P_{tr}$
	Nighttime	$41.282 + 0.087 \times S_f + 0.735 \times P_{tr} - 0.006 \times V - 0.027 \times V \times P_{tr}$

* P_{tr} – Truck percentage. S_f – Free-flow speed (mph). V – Volume in work zone (vph)

An example is presented to illustrate how the regression models can be used to estimate the expected speed in work zones under a certain speed control strategy and traffic condition and therefore compare the performance of strategies. Assume a hypothetical work zone segment with free-flow speed of 65 mph, volume of 1000 vph, and truck percentage of 5 percent. The expected speeds calculated from the models in Table 5 are shown in Table 6. Hence, the regression models provide a convenient approach for engineers to determine the speed control strategy while considering traffic conditions in combination with speed control strategies.

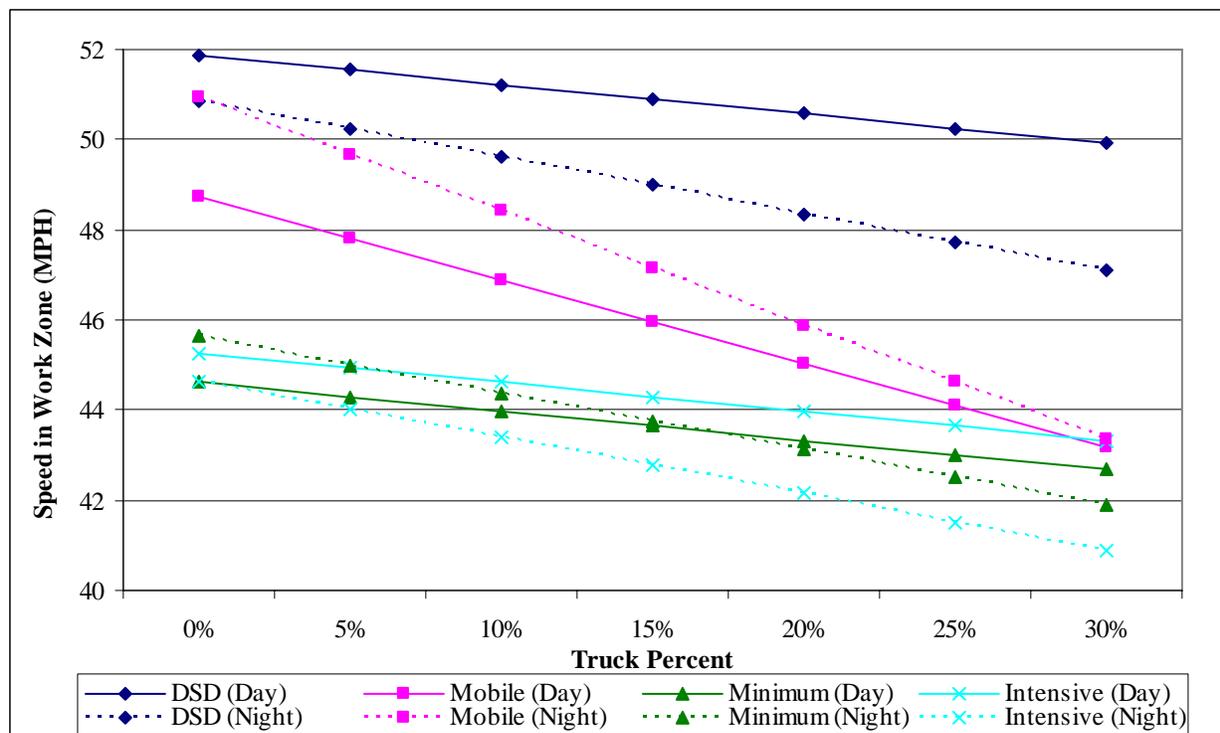


FIGURE 6 Estimated speed in work zone under speed control strategies.

TABLE 6 Estimated Speed in Work Zone under Four Speed Control Strategies (Example)

Strategy	Daytime (mph)	Nighttime (mph)
DSD	51	50
Mobile Enforcement	46	48
Minimum Enforcement	44	45
Intensive Enforcement	45	44

CONCLUSIONS

Two types of speed management strategies, namely DSD and enforcement, were evaluated at STH 29 and STH 164 work zones in Wisconsin. After a long-term implementation, the DSD had a slight impact on the daytime speed but significantly decreased both the average speed and percentage of speeding drivers during nighttime hours. The significant speed reduction by the DSD presented in previous studies was likely the result of a novelty effect. As observed in this study, the overall speed reduction lapsed with time. The lack of enforcement support was another critical factor contributing to the limited effectiveness of the DSD. Enforcement ranked as one of the most effective strategies in controlling speed in work zones. Due to the fact that upstream and work zone activity area had the same speed limit, limited speed reduction was observed in this study. Although the reductions were relatively small from the engineering or practical standpoint, mobile enforcement led to significant reductions in average speed in daytime and intensive enforcement accomplished the same in nighttime, which suggests that a combination of various enforcement methods may yield the best result for work zone speed management. Additionally, it was demonstrated that intensive enforcement encouraged more

high-speed drivers to reduce operating speeds in work zones. The number of citations was found to partially account for the reduction in speeders at night due to the police officers' visibility.

Regression analysis indicated that free-flow speed, time of day, volume and truck percentage confound with speed control strategies in affecting the operating speed in work zones. Specifically, higher free-flow speed and lower volume induce higher speed in work zone under all of the strategies. On the other hand, higher truck percentage leads to a lower work zone speed. Further, a new approach was proposed to compare the performance of varied speed control strategies using a regression model, and therefore, to assist in the selection of the appropriate traffic control strategies under a certain traffic condition.

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