Safety Evaluation of STOP AHEAD Pavement Markings

U.S. Department of Transportation
Federal Highway Administration

FOREWORD

The goal of this research was to evaluate and estimate the safety effectiveness of STOP AHEAD pavement marking as one of the strategies in the Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS), Phase I.

This research provides Crash Reduction Factor (CRF) and economic analysis for the effectiveness of STOP AHEAD pavement marking strategy. The estimate of effectiveness for the STOP AHEAD pavement marking strategy was determined by conducting scientifically rigorous before-after evaluations at sites where this strategy was implemented in the United States.

The above safety improvement and all other targeted strategies in the ELCSI-PFS are identified as low-cost strategies in the *NCHRP Report 500* guidebooks. Participating States in the ELCSI-PFS are Arizona, California, Connecticut, Florida, Georgia, Illinois, Indiana, Iowa, Kansas, Kentucky, Maryland, Massachusetts, Minnesota, Mississippi, Montana, New York, North Carolina, North Dakota, Oklahoma, Pennsylvania, South Carolina, South Dakota, Tennessee, Texas, Utah, and Virginia.

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16. Abstract
The Federal Highway Administration (FHWA) organized a Pooled Fund Study of 26 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. One of the strategies chosen to be evaluated for this study was STOP AHEAD pavement markings. This strategy is intended to reduce the frequency of crashes related to driver unawareness of stop-control at unsignalized intersections.

Geometric, traffic, and crash data were obtained at unsignalized intersections for 8 sites in Arkansas, 9 sites in Maryland, and 158 sites in Minnesota. To account for potential selection bias and regression-to-the-mean, an empirical Bayes before-after analysis was conducted to determine the safety effectiveness of installing STOP AHEAD pavement markings. Results of the aggregate analysis indicate a statistically significant reduction in total crashes for Arkansas, Maryland, and the two States combined. The combined aggregate analysis indicates that at least a 15-percent reduction in total crashes can be expected conservatively. There is also a statistically significant reduction in right-angle and rear-end crashes for Arkansas. A reduction in injury crashes is shown for Arkansas and Maryland and is statistically significant at the ten percent level for the two States combined. The results for Minnesota were not included in the main analysis, but support the conclusion that this strategy is safety effective. The disaggregate analysis indicated that crash reductions are highly significant at three-legged intersections and significantly greater than reductions at four-legged intersections. The strategy was also more effective at intersections with all-way stop-control (AWSC). Given the low-cost of this strategy, even with conservative assumptions, a modest reduction in crashes is needed to justify their use. Based on the estimated safety effectiveness of STOP AHEAD pavement markings, the necessary crash reduction to obtain a 2:1 benefit-cost ratio is easily achieved. Therefore, this strategy has the potential to reduce crashes cost-effectively at unsignalized intersections, particularly at three-legged and AWSC intersections.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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ABBREVIATIONS AND SYMBOLS

Abbreviations

A	Injury, incapacitating
AADT	Average annual daily traffic
AASHTO	American Association of State Highway Transportation Officials
ADT	Average daily traffic
AHTD	Arkansas State Highway and Transportation Department
AWSC	All-way stop-control
B	Injury, nonincapacitating
C	Possible injury
EB	Empirical Bayes
FHWA	Federal Highway Administration
ft	Feet
HLR	Highway Location Reference
HSIS	Highway Safety Information System
KABCO	Scale used to represent injury severity in crash reporting
K	Fatality
MDSHA	Maryland State Highway Administration
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
O	Property damage only
OWSC	One-way stop-control
S.E.	Standard error
SPF	Safety performance functions
STATA	Software package
Stddev	Standard deviation
TRB	Transportation Research Board
TWSC	Two-way stop-control
Var	Variance

Symbols

α	Greek letter Alpha
β	Greek letter Beta
Δ	Greek letter Delta
λ	Greek letter Lamda
π	Greek letter Pi
θ	Greek letter Theta

EXECUTIVE SUMMARY

The Federal Highway Administration (FHWA) organized a Pooled Fund Study of 26 States to evaluate low-cost safety strategies as part of its strategic highway safety effort. The purpose of the FHWA Low-Cost Safety Improvements Pooled Fund Study is to evaluate the safety effectiveness of several of the low-cost safety strategies through scientifically rigorous crash-based studies. One of the strategies chosen to be evaluated for this study was STOP AHEAD pavement markings. This strategy is intended to reduce the frequency of crashes related to lack of driver awareness of stop-control at unsignalized intersections. The safety effectiveness of this strategy had not previously been thoroughly documented, and this study is an attempt to provide an evaluation through scientifically rigorous procedures.

Geometric, traffic, and crash data were obtained at unsignalized intersections for 8 sites in Arkansas, 9 sites in Maryland, and 158 sites in Minnesota. In Minnesota, this was a blanket strategy in two counties. This was not a blanket strategy in Arkansas and Maryland; the strategy was implemented as a safety improvement on a case-by-case basis. To account for potential selection bias and regression-to-the-mean, an Empirical Bayes (EB) before-after analysis was conducted to determine the safety effectiveness of installing STOP AHEAD pavement markings.

Results of the aggregate analysis indicate a statistically significant reduction in total crashes for Arkansas, Maryland, and the two States combined. The combined analysis indicates that, conservatively, a reduction in total crashes of at least 15 percent can be expected after the installation of STOP AHEAD pavement markings. There is also a statistically significant reduction in right-angle and rear-end crashes for Arkansas. The results for Minnesota were not included in the main analysis because of the low crash rates at those sites. The disaggregate analysis indicates that crash reductions are highly significant at three-legged intersections and are significantly greater than reductions at four-legged intersections. The strategy is also more effective at intersections with all-way stop-control (AWSC).

Given the low cost of this strategy, even with conservative assumptions, a modest reduction in crashes is needed to justify their use. Based on the estimated safety effectiveness of STOP AHEAD pavement markings, the necessary crash reduction to obtain a 2:1 benefit-cost ratio is easily achieved. Therefore, this strategy has the potential to reduce crashes cost effectively at stop-controlled intersections, particularly at three-legged and AWSC intersections.

INTRODUCTION

Background on Strategy

Intersections account for a small portion of the total highway system, yet in 2005, approximately 2.5 million intersection-related crashes occurred. Intersection crashes accounted for 41 percent of all reported crashes and 22 percent (8,655) of all fatal crashes in 2005.[1] The disproportionately high percentage of intersection crashes is not surprising because intersections present more points of conflict than non-intersection locations. Of the total intersection-related crashes, about 51 percent (1.27 million) occur at unsignalized intersections, of which 5,882 involve a fatality. This is compared to the 1.25 million crashes at signalized intersections, which includes 2,773 fatal crashes.[1]

Driver compliance with intersection traffic control is vital to intersection safety. The typical location of unsignalized intersections, however, presents several challenges. The majority of unsignalized intersections are located along low- to moderate-volume roads in rural and suburban areas that are generally associated with high-speed travel and relatively lower geometrics than those in more developed suburban and urban areas.[2] Many unsignalized intersections may be unexpected or may not be visible to approaching drivers. Therefore, enhancing the visibility and conspicuity of unsignalized intersections has the potential to reduce the number of crashes associated with drivers' lack of awareness of the intersection.

Providing pavement markings with supplementary messages (e.g., STOP AHEAD) can help alert drivers on the stop-controlled approach to the presence of an intersection. These markings may be particularly appropriate for unsignalized intersections with patterns of rear-end or right-angle collisions related to lack of driver awareness of the intersection.[2] An example of a STOP AHEAD pavement marking is shown in figure 1. The success of this strategy will rely on selecting appropriate locations for applying the pavement markings. For example, these markings may be most effective at specific locations such as rural intersections with two-way stop-control. The visibility and, therefore, maintenance is also critical to the effectiveness of supplementary pavement markings. The installation or upgrade of any pavement markings should follow the guidelines in the *Manual on Uniform Traffic Control Devices* (MUTCD).[3]

Figure 1. Example of a Rural STOP AHEAD Installation.

Background on Study

In 1997, the American Association of State Highway and Transportation Officials (AASHTO) Standing Committee for Highway Traffic Safety, with the assistance of the Federal Highway Administration (FHWA), the National Highway Traffic Safety Administration (NHTSA), and the Transportation Research Board (TRB) Committee on Transportation Safety Management, met with safety experts in the field of driver, vehicle, and highway issues from various organizations to develop a strategic plan for highway safety. These participants developed 22 key areas that affect highway safety. One of these areas is unsignalized intersection crashes.

The National Cooperative Highway Research Program (NCHRP) published a series of implementation guides to advance the implementation of countermeasures targeted to reduce crashes and injuries. Each guide addresses 1 of the 22 emphasis areas and includes an introduction to the problem, a list of objectives for improving safety in that emphasis area, and strategies for each objective. Each strategy is designated as proven, tried, or experimental. Many

of the strategies discussed in these guides have not been rigorously evaluated; about 80 percent of the strategies are considered tried or experimental.

The FHWA organized a Pooled Fund Study of 26 States to evaluate low-cost safety strategies as part of this strategic highway safety effort. The purpose of the Pooled Fund Study is to evaluate the safety effectiveness of several tried and experimental, low-cost safety strategies through scientifically rigorous crash-based studies. Installing STOP AHEAD pavement markings at unsignalized intersections was selected as a strategy to be evaluated as part of this effort.

Literature Review

The safety effectiveness of STOP AHEAD pavement markings has not been adequately quantified. The literature did not uncover any studies that specifically evaluated the safety effectiveness of STOP AHEAD pavement markings. Research has indicated that increases in intersection-related crashes are associated with horizontal and vertical curvature among other variables.[4] STOP AHEAD pavement markings can warn drivers of unexpected intersections and have the potential to reduce intersection crashes where sight distance or driver awareness is an issue. Several studies have been conducted to determine the effectiveness of STOP AHEAD signs as prescribed by MUTCD,[5] but did not address their effectiveness in reducing crashes. Zwahlen studied the effectiveness of STOP AHEAD signs as a means of warning drivers of an upcoming, unexpected, and partially concealed stop-controlled intersection during daytime and nighttime driving conditions.[6] Drivers approached the STOP sign with lower average speeds and lower average longitudinal decelerations at night when the STOP AHEAD sign was present than when it was not present. Although the STOP AHEAD sign was shown to influence driver behavior at night, eight of ten improper stops occurred when the STOP AHEAD sign was present. Although the study concluded that STOP AHEAD signs do not give drivers adequate visual stimulus to prepare them to stop when approaching an unexpected, partially concealed intersection, the STOP AHEAD pavement markings may provide better visual stimulus to the driver due to the size and placement of the message. It is clear that a thorough investigation is needed to evaluate the effectiveness of STOP AHEAD pavement markings in reducing crash frequency and severity for different configurations of unsignalized intersections.

OBJECTIVES

This research examined the safety impacts of STOP AHEAD pavement markings at unsignalized intersections in Arkansas, Maryland, and Minnesota. The initial objective was to identify sites with crashes related to unexpected or partially concealed STOP signs in the before period and estimate the expected change in crashes due to implementing the STOP AHEAD pavement marking using the EB method. It was not possible to determine those sites that were treated due to limited intersection visibility. Although "safety" and "liability" issues were stated as reasons for installation, "limited sight distance" was not stated explicitly for each case. In addition, this was a blanket strategy in the two counties included from Minnesota. Therefore, the objective was modified to estimate the general safety effectiveness of this strategy as measured by crash frequency. Target crash types included the following:

- Total intersection crashes.

- Injury crashes (i.e., K, A, B, and C injuries on KABCO scale).

- Right-angle (side impact) crashes.

- Rear-end crashes.

It was noted that the range of safety effects may vary by crash type and intersection type. Therefore, a second objective was to determine whether the effects vary by the following:

- Traffic volumes.

- Land use.

- Number of approaches.

- Number of stop-controlled approaches.

The final objective was to estimate the overall effectiveness of the strategy. The measure of overall effectiveness included the installation costs and crash savings. Crash savings were broken-down by crash type and severity using crash costs recently developed by FHWA. Meeting these objectives placed some special requirements on the data collection and analysis tasks including the following:

- The need to select a large enough sample size to detect, with statistical significance, what may be small changes in safety for some crash types.

- The need to identify appropriate reference sites.

- The need to properly account for traffic volume changes.

- The need to pool data from multiple jurisdictions to improve reliability of the results and facilitate broader applicability of the products of the research.

STUDY DESIGN

The study design involved a sample size analysis and prescription of needed data elements. The sample size analysis assessed the size of sample required to statistically detect an expected change in safety and also determined what changes in safety can be detected with likely available sample sizes.

Sample Size Overview

Basic to estimating sample sizes are assumptions related to the expected safety effects and the crash frequency at STOP AHEAD sites in the before period. Minimum and desired sample sizes were calculated assuming a conventional before-after study with reference group, as described in Hauer,[7] and a literature review of likely crash rates. The sample size analysis undertaken for this study addresses the size of sample required to statistically detect an expected change in safety. The sample size estimates are conservative because the EB methodology is incorporated in the before-after analysis rather than applying a conventional before-after analysis with reference group.

Sample sizes were estimated for various assumptions of likely safety effects and crash frequencies in the before period. Crash rates were assumed for three crash types (i.e., total, right-angle, and rear-end). As shown in table 1, a low (0.44 crashes/intersection/year), moderate (3.45 crashes/intersection/year), and high (7.62 crashes/intersection/year) crash rate for total crashes were assumed based on a variety of sources including previous studies, SafetyAnalyst,[8] and the Highway Safety Information System (HSIS).[9] It was then assumed that right-angle and rear-end collisions represent 39 percent and 23 percent of total crashes, respectively, based on data from SafetyAnalyst.[8] To facilitate the analysis, it was also assumed that the number of reference sites is equal to the number of strategy sites. The sample size estimates provided would be conservative in that state-of-the-art EB methodology proposed for the evaluations would require fewer sites.

Intersection-years are the number of intersections where the strategy was applied multiplied by the number of years the strategy was in place at each intersection. For example, if a strategy was applied at nine intersections and has been in place for three years at all nine intersections, there are a total of 27 intersection-years available for the study.

Table 1. Before Period Crash Rate Assumptions.

Crash Type	Rate A (crashes/ intersection/year)	Rate B (crashes/ intersection/year)	Rate C (crashes/ intersection/year)
All	3.45	7.62	0.44
Right-angle (39% of total assumed)	1.35	2.97	0.17
Rear-end (23% of total assumed)	0.79	1.75	0.10

Table 2 provides estimates of the required number of before and after period site-years for both the 90-percent and 95-percent confidence levels. The minimum sample indicates the level for which a study seems worthwhile; that is, it is feasible to detect with 90-percent confidence the largest effect that may reasonably be expected based on what is currently known about the strategy. In this case, a 20-percent reduction in total crashes was assumed as this upper limit on safety effectiveness. The desirable sample assumes that the reduction could be as low as 10 percent for total crashes, and this is the smallest benefit that one would be interested in detecting with 90-percent confidence. The logic behind this approach is that safety managers may not want to implement a measure that reduces crashes by less than 10 percent and the sample size required to detect a reduction smaller than 10 percent would likely be prohibitively large. These sample size calculations were based on specific assumptions regarding the number of crashes per intersection and years of available data.

The values recommended in this study are highlighted in bold. A minimum sample size of 53 intersection-years and a desirable sample size of 260 intersection-years per period were calculated. The calculations assume an equal number of site-years for the strategy and reference

sites and an equal length of before and after periods. These selections assume that the reduction in crashes in each case could be as low as a 10-percent reduction in all crashes and that this is the smallest benefit that one would be interested in detecting with 90-percent confidence. Estimates may be predicted with greater confidence or a smaller reduction in crashes will be detectable if it turns out that there are more intersection-years of data available in the after period. The same holds true if there is a higher crash rate than expected in the before period.

Table 2. Minimum Required Before Period Site-Years for Treated Sites for Crash Rate Assumptions.

Expected Percent Reduction in Crashes		95% Confidence			90% Confidence		
		A	B	C	A	B	C
All	5	1,629	738	127,73	1,141	516	8,943
	10	371	168	2,907	**260**	118	2,036
	20	76	34	594	**53**	24	416
	30	27	12	211	19	9	147
	40	12	5	92	8	4	64
Right-Angle	5	4,163	1,892	33,060	2,915	1,325	23,146
	10	948	431	7,525	663	302	5,268
	20	194	88	1,537	135	62	1,076
	30	69	31	545	48	22	381
	40	30	14	237	21	10	166
Rear-End	5	7,114	3,212	56,203	4981	2,249	39,349
	10	1,619	731	12,793	1,134	512	8,956
	20	331	149	2,612	232	105	1,829
	30	117	53	926	82	37	648
	40	51	23	403	36	16	282

Note: The bold denotes values recommended in this study.

It was necessary to identify a suitable reference group to be used in the EB procedure. As a general rule of thumb, 30 reference sites are identified for each major category (e.g., rural/urban and three-legged/four-legged) within the strategy sites for each State. For example, if the strategy was implemented in both rural and urban areas at both three- and four-legged intersections, there are four major categories (rural, three-legged; rural, four-legged; urban, three-legged; and urban, four-legged). If the strategy was only in rural areas, the number of categories would be reduced to just two major groups (rural, three-legged and rural, four-legged). Based on the study design, it was estimated that a maximum of 120 reference sites for each State would be needed for the EB analysis.

METHODOLOGY

The EB methodology for observational before-after studies[7] was used for the evaluation. This methodology is rigorous in that it addresses the following:

- It properly accounts for regression-to-the-mean.

- It overcomes the difficulties of using crash rates in normalizing for volume differences between the before and after periods.

- It reduces the level of uncertainty in the estimates of safety effect.

- It provides a foundation for developing guidelines for estimating the likely safety consequences of contemplated strategy.

- It properly accounts for differences in crash experience and reporting practice in amalgamating data and results from diverse jurisdictions.

In the EB approach, the change in safety for a given crash type at a site is given by:

$$\Delta \text{ Safety} = \lambda - \pi , \qquad (1)$$

Where:

λ is the expected number of crashes that would have occurred in the after period without strategy.

π is the number of reported crashes in the after period.

In estimating λ, the effects of regression-to-the-mean and changes in traffic volume were explicitly accounted for using safety performance functions (SPFs) relating crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated sites (reference sites). Annual SPF multipliers were calibrated to account for the temporal effects (e.g., variation in weather, demography, and crash reporting) on safety.

In the EB procedure, the SPF is used to first estimate the number of crashes that would be expected in each year of the before period at locations with traffic volumes and other characteristics similar to the one being analyzed (i.e., reference sites). The sum of these annual

SPF estimates (P) is then combined with the count of crashes (x) in the before period at a strategy site to obtain an estimate of the expected number of crashes (m) before strategy. This estimate of m is:

$$m = w_1(x) + w_2(P),$$

(2)

Where:

    w_1 and w_2 are estimated from the mean and variance of the SPF estimate as:

$$w_1 = \frac{P}{P + 1/k},$$

(3)

$$w_2 = \frac{1}{k(P + 1/k)},$$

(4)

Where:

    k is a constant for a given model and is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In that process, a negative binomial distributed error structure is assumed with k being the dispersion parameter of this distribution.

A factor is then applied to m to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by P, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance of λ.

The estimate of λ is then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes during the after period in that group (π_{sum}). The variance of λ is also summed over all sites in the strategy group.

The Index of Effectiveness (θ) is estimated as:

$$\theta = \frac{\pi_{sum}/\lambda_{sum}}{1 + \left(Var(\lambda_{sum})/\lambda_{sum}^2\right)}.$$

(5)

The standard deviation of θ is given by:

$$StDev(\theta) = \sqrt{\frac{\theta^2\left(\dfrac{Var(\pi_{sum})}{\pi_{sum}^2} + \dfrac{Var(\lambda_{sum})}{\lambda_{sum}^2}\right)}{\left(1 + \dfrac{Var(\lambda_{sum})}{\lambda_{sum}^2}\right)^2}} .$$

(6)

The percent change in crashes is calculated as $100(1-\theta)$; thus, a value of $\theta = 0.7$ with a standard deviation of 0.12 indicates a 30-percent reduction in crashes with a standard deviation of 12 percent.

DATA COLLECTION

Arkansas, Maryland, and Minnesota provided installation data, including locations and dates for installations of STOP AHEAD pavement markings. These States also provided roadway geometry, traffic volumes, and crash data for both installation and the reference sites. This section provides a summary of the data assembled for the analysis.

Arkansas

Background

The Arkansas State Highway and Transportation Department (AHTD) installed STOP AHEAD pavement markings to increase safety at stop-controlled intersections throughout the State. The intersections included in this evaluation were identified as having a crash problem. STOP AHEAD pavement markings were installed after the State reviewed the sites and determined that noncompliance with the traffic control was a contributing factor to the crashes occurring at these intersections.

In the past, the AHTD painted the STOP AHEAD pavement markings on the roadway, but for the last few years they have used thermoplastic panels that are applied to the pavement using heat. The average cost of the thermoplastic markings is approximately $765 per approach, which includes materials, equipment, and labor. The thermoplastic markings can last five years if applied in good conditions while the expected life of painted markings is only one to two years. Good installation conditions include a dry roadway surface, warm temperatures, and new pavement. Relatively new pavements hold the markings better than older asphalt or Portland concrete pavements, which are not as coarse and porous. Another advantage of the thermoplastic is that the application process is much shorter; thermoplastic only has to cool for a few minutes after being applied as opposed to painted markings, which take longer.

Installation Data

AHTD paper maintenance records were used to identify 14 strategy locations. The date of the maintenance record was used to determine the approximate date of installation. The maintenance records did not contain the exact installation dates. According to the AHTD representative, the

pavement markings were installed during the 60-day window from the date of the maintenance record. District engineers provided the section, route, and log miles of the intersection. When available, data on other strategies installed at the study locations were collected.

Reference Sites

AHTD provided a list of unsignalized intersections. The project team compared this list with data available in AHTD's roadway inventory, Roadlog, to develop a list of unsignalized intersections to use as reference sites. Roadlog is a database of State, U.S., and Interstate roadway information that is maintained by the AHTD.

Roadlog does not contain information on the stop-control at individual intersections. AHTD provided the following guidance to determine stop-control at the reference sites:

- Four-legged intersections:

  o If the ADT on the major road is approximately twice that of the minor road, then the intersection is classified as two-way stop-controlled with STOP signs on the minor road approaches.

  o If the ADT of the major and minor roads are comparable, then the intersection is classified as all-way stop-controlled with STOP signs on all approaches.

- Three-legged intersections:

  o If the ADT on the major road is approximately twice that of the minor road, then the intersection is classified as one-way stop-controlled with a STOP sign on the minor road approach.

  o If the ADT of major and minor roads are comparable, then the intersection is classified as all-way stop-controlled with STOP signs on all approaches.

Aerial photographs available through Google^{TM} Earth provided visual information that was used to verify the placement of stop-control when possible.

Roadway Data

Roadlog was used to obtain roadway information by specifying the district, county, route and section for each roadway segment. Each link in the Roadlog system is defined by a starting and ending milepost, which typically correspond to a named major cross street or a geographic feature such as a county line. The major cross-street name and milepost were used to obtain roadway information for each approach. Roadway characteristics included the number of lanes, lane width, shoulder presence, average annual daily traffic (AADT), and area type (urban/rural).

Traffic Data

Roadlog contains AADT for 2004. The AHTD Web site contains AADT data for 2005 and years prior to 2004. Annual growth factors were computed and used to add missing AADT data.

AADT data were not available for some minor approaches; it was not possible to apply the growth factor in these cases.

Crash Data

The Traffic Safety Section of the AHTD Planning and Research Division provided crash data for the entire State from 1994 to 2004. There were several formatting changes to the crash data throughout the 11-year period. AHTD provided the necessary codebooks to interpret and adjust the data for the 11-year period. A radius of 76.25 m (250 ft) was used to identify crashes at the strategy and reference intersections.

Maryland

Background

The Maryland State Highway Administration (MDSHA) installed STOP AHEAD markings on State highway and intersecting local road approaches between 1999 and 2004 in response to past safety performance (i.e., number of crashes) or site-specific safety concerns (i.e., sight distance limitations due to vertical or horizontal curve). The supplemental pavement markings are an attempt to break the monotony of long stretches of road in order to indicate the presence of a STOP sign.

The markings are typically heat applied, pre-form thermoplastic that are expected to last four to seven years, depending on weather conditions and the amount of traffic. The lettering is typically eight feet in both length and width, with spacing between the "STOP" and "AHEAD" markings of 812.8 mm (32 inches) to 2,286 mm (90 inches) depending on the speed of vehicles on the roadway. An example of the layout of a STOP AHEAD pavement marking is shown in figure 2. The average cost of installation is approximately $15 per square foot, equating to about $1,500 per STOP AHEAD message.

Installation Data

MDSHA provided installation locations for 15 intersections where STOP AHEAD pavement markings were installed throughout the State. Another five locations were identified in District 3 by reviewing the District's video log database, a program called VisiData. Based on availability of installation dates, only 9 of the 20 total sites could be used in the evaluation. When available, data on other strategies installed at the study locations were collected. Several of the study locations in Maryland had STOP AHEAD warning signs installed in addition to the pavement markings as shown in figure 2.

Figure 2. STOP AHEAD Pavement Marking with Warning Sign.

Reference Sites

MDSHA identified 60 reference sites. These reference sites were selected based on the availability of information (traffic counts, roadway geometry, etc.) and are reflective of the study site characteristics.

Roadway Data

Initial data collection was conducted utilizing the MDSHA Highway Location Reference (HLR) system. HLR is available online and covers the most commonly requested data elements on road segments in the MDSHA system. The HLR provides both physical data (e.g., AADT and number of lanes) and administrative data (e.g., milepost and functional class). The HLR data can be used in conjunction with VisiData by matching the route and milepost numbers to obtain a robust understanding of the physical and administrative characteristics of a particular segment.

This information was augmented by field visits. The area type (i.e., urban or rural), lane width, presence and width of the shoulder, and speed limit for each intersection approach were obtained with field visits.

Traffic Data

The MDSHA Web site provided AADT data by year from 1988 to 2006 stratified by route number, mile number, and intersection description (e.g., intersection name or distance to intersection). Counts are not often available directly at an intersection. If the subject intersection was located between two count locations, an average of the two closest counts was computed. If the count location was relatively close to the subject intersection, the closest count was used. An

annual growth factor was computed and applied to the traffic volumes to fill-in the AADT data for years that were not available.

Roads that were not maintained by the State posed a greater challenge for volume data collection. The county or city where the site was located was contacted to obtain volume data if State data were not available. Montgomery County provided access to their county-maintained turning movement count database. Volumes were adjusted using the MDSHA factors to convert the turning movement counts into AADTs.

Crash Data

MDSHA provided crash data for all nine study locations and 60 reference site locations for the years 1996 through 2005 reported. Specific variables were requested to determine the details of each crash (e.g., crash type, severity, weather, etc.). Crashes that occurred on all approaches within 76.3 m (250 ft) of the intersection were included.

Minnesota

Background

The Minnesota Department of Transportation installed STOP AHEAD markings to address safety and liability concerns at unsignalized intersections. Two counties, Douglas and Otter Tail, provided installation data. In Otter Tail County, the pavement markings were installed on the minor approaches of all two-way, stop-controlled intersections along county highways. In Douglas County, the pavement markings were installed in advance of all two-way, stop-controlled intersections where the speed limit was 64.4 km/h (40 mi/h) or greater.

The markings are Diamond Vogel latex paint with message beads and are applied using templates and a cart mounted sprayer. The latex markings are expected to last one to four years, depending on weather conditions and the amount of traffic. The STOP AHEAD pavement markings are repaved at a 50-percent wear point. This can be one year for higher volume roads, and up to four years on lower volume roads. The lettering is typically 2.4 m (8 ft) in length. The average cost of installation is approximately $125 per STOP AHEAD message.

Installation Data

Engineers in Douglas and Otter Tail Counties provided installation data for STOP AHEAD pavement markings installed between 1998 and 2004. Although additional counties in the State have installed this strategy, they were not able to provide installation locations and dates. Otter Tail County provided the greatest number of sites (152) followed by Douglas County (12 sites). Of the 164 strategy locations provided by Otter Tail and Douglas Counties, 158 intersections were included in the evaluation. The primary motivation for selecting these 158 intersections was the availability of roadway and traffic volume data. When available, data on other strategies installed at the study locations were collected.

Reference Sites

Data for 401 additional sites were obtained from Minnesota as a reference group that did not receive the STOP AHEAD strategy or other countermeasures aimed at reducing intersection-

related crashes. These sites were similar to the study intersections in geometry, volume, and location.

Roadway Data

The Highway Safety Information System (HSIS) provided the necessary roadway data for all strategy and reference sites.[9] The *Guidebook for the Minnesota State Data Files* provides information on the availability and accuracy of the data.[10] Data are available through HSIS for the location (milepost, functional class) and physical characteristics (AADT, number of lanes) of the roadway. Each roadway segment or intersection is identified by route number and milepost, which can be matched to the corresponding crashes.

Traffic Data

The HSIS Minnesota intersection database served as the source of the traffic volume data.[9] The *Guidebook for the Minnesota State Data Files*[10] cautions that traffic volume data are not always available for the current year in the intersection file. The *Guidebook for the Minnesota State Data Files* does not provide a method for interpolating accurate and reliable traffic volume data. Therefore, a method for estimating the traffic volume at each intersection was developed. The traffic volumes were calculated consistently for strategy and reference sites using the intersection traffic volume data and the following steps:

- Divide the traffic volume by 2 for each approach to obtain the one-way traffic volume.

- Estimate annual growth factors using most complete years of traffic volume data.

- Fill-in missing traffic volume data using the annual growth factors from step 2.

- Sum the one-way traffic volumes for opposing approaches to obtain an estimate of the major and minor approach traffic volumes.

An estimate of the total entering traffic volume was developed for each year of the study period for the strategy and reference sites.

Crash Data

The HSIS Minnesota crash database served as the source of the crash data at three levels (crash-based, vehicle-based, and driver-based). Each crash is associated with a unique identification number that can be used to link the three levels of crash data. The crash data are also located by route and milepost, which can be used to link the crash data to the corresponding roadway segment or intersection. Crashes that occurred, on any approach, within 76.25 m (250 ft) of the intersection were included in the analysis.

Summary of Data

Table 3 provides crash definitions used in the three States. This information is crucial in applying the safety effect estimates in other jurisdictions. Tables 4 through 6 provide summary information for the data collected in each State.

Table 3. Definitions of Crash Types.

State	Intersection-Related	Injury	Right-Angle	Rear-End
AR	Within 250 ft of intersection	K, A, B, or C on KABCO scale	Defined as angle	Defined as rear-end
MD	Within 250 ft of intersection	K, A, B, or C on KABCO scale	Defined as angle or turning-intersecting paths	Defined as rear-end
MN	Within 250 ft of intersection	K, A, B, or C on KABCO scale	Defined as right-angle	Defined as rear-end

1 ft = 0.305 m

Table 4. Data Summary for Arkansas Sites (n = 8).

Variable	Mean	Minimum	Maximum
Months before	102.9	82.3	127.3
Months after	32.1	16.7	49.7
Intersection-years before	8.6	6.9	10.6
Intersection-years after	2.7	1.4	4.1
Crashes/site-year before	1.60	0.13	7.78
Crashes/site-year after	1.36	0.00	9.00
Injury crashes/site-year before	0.86	0.00	4.44
Injury crashes/site-year after	1.08	0.00	7.50
Right-angle crashes/site-year before	0.82	0.00	5.00
Right-angle crashes/site-year after	0.81	0.00	6.50
Rear-end crashes/site-year before	0.32	0.00	1.78
Rear-end crashes/site-year after	0.04	0.00	0.34
Total Entering AADT before	5,330	407	11,284
Total Entering AADT after	5,588	513	11,850

Table 5. Data Summary for Maryland Sites (n = 9).

Variable	Mean	Minimum	Maximum
Months before	79.0	44.7	107.9
Months after	41.0	12.1	75.3
Intersection-years before	6.6	3.7	9.0
Intersection-years after	3.4	1.0	6.3
Crashes/site-year before	3.71	0.22	7.19
Crashes/site-year after	2.83	0.00	7.00
Injury crashes/site-year before	2.18	0.11	4.29
Injury crashes/site-year after	1.34	0.00	3.20
Right-angle crashes/site-year before	1.49	0.00	3.81
Right-angle crashes/site-year after	1.06	0.00	3.60
Rear-end crashes/site-year before	0.58	0.00	1.68
Rear-end crashes/site-year after	0.59	0.00	2.00
Total Entering AADT before	8,094	1,627	14,043
Total Entering AADT after	8,856	1,663	17,263

Table 6. Data Summary for Minnesota Sites (n = 158).

Variable	Mean	Minimum	Maximum
Months before	117.0	36.0	120.0
Months after	26.1	24.0	96.0
Intersection-years before	9.8	3.0	10.0
Intersection-years after	2.2	2.0	8.0
Crashes/site-year before	0.04	0.00	0.67
Crashes/site-year after	0.01	0.00	0.63
Injury crashes/site-year before	0.02	0.00	0.40
Injury crashes/site-year after	0.00	0.00	0.20
Right-angle crashes/site-year before	0.01	0.00	0.30
Right-angle crashes/site-year after	0.00	0.00	0.33
Rear-end crashes/site-year before	0.00	0.00	0.10
Rear-end crashes/site-year after	0.00	0.00	0.17
Total Entering AADT before	756	80	6,076
Total Entering AADT after	858	88	6,310

These tables indicate a total sample of 1,669 intersection-years of data (69 intersection-years from Arkansas, 59 intersection-years from Maryland, and 1,541 intersection-years from Minnesota). The desired sample size was 260 intersection-years to detect a 10-percent reduction in all crashes. Although the actual sample in terms of intersection-years exceeds this value, it should be noted that more sites are required than originally estimated since the before-period crash rate for Minnesota and Arkansas are much lower than the 3.45 crashes per intersection-year assumed in the study design. However, for Maryland, the crashes per intersection-year in the before period is similar to what was assumed in the study design. Therefore, the actual sample size for Maryland of 59 intersection-years alone compares favorably to the minimum sample size of 53 intersection-years required to detect a 20-percent reduction in all crashes. On this basis, the sample was adequate to proceed with the analysis.

Table 6 indicates that the minimum after period was two years and the maximum was eight years for Minnesota. Arkansas indicated a service life of one to two years and Minnesota indicated a service life of one to four years for the latex STOP AHEAD application. While the after period

exceeds the service life of the strategy for some intersections, it was assumed that the pavement markings were maintained throughout the study period. This assumption was based on the fact that the States provided maintenance costs in addition to the installation costs, indicating that the pavement markings are not a one-time installation.

DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

This section presents the safety performance functions (SPFs) developed for each State. The SPFs are used in the EB methodology[7] to estimate the safety effectiveness of this strategy. Generalized linear modeling was used to estimate model coefficients using the software package STATA[®(11)] and assuming a negative binomial error distribution, which is consistent with the state of research in developing these models.

SPFs were calibrated separately for Arkansas, Maryland, and Minnesota using the corresponding reference sites from each State. The approach taken was as follows:

- Use the reference site data to develop SPFs.

- Recalibrate each SPF separately for the before and after periods to develop yearly multipliers.

Since the installations were over a multi-year period it was possible to represent yearly trends in crash counts in an unbiased way which would not be possible if all installations occurred in the same year.

The primary form of the SPFs is:

$$\text{Crashes/year} = \alpha \, (\text{AADT})^{\beta 0} \tag{7}$$

Where:

        AADT   is the total entering AADT.

        α and $\beta 0$ are parameters estimated from data in the SPF calibration process.

Preliminary models were developed using several forms of AADT including separate terms for major and minor AADT, total entering AADT (major plus minor), and the product of major and minor AADT. The study team determined that total entering AADT was the most appropriate form of AADT for Arkansas and Minnesota. This decision was based on an evaluation of parameter estimates (i.e., how well the parameter estimates compared to past studies).

For Maryland, there were a number of reference and strategy sites where AADT could not be obtained for the minor approaches. Therefore, two separate models were developed using the Maryland reference sites and applied to the strategy sites based on the availability of data. The first model included all reference sites and used the major AADT in place of total entering AADT in equation 7. The second model included a subset of the reference sites; those where AADT was available for the major and minor road. The second model was developed using total entering AADT, similar to the models from Arkansas and Minnesota. A reasonable model could not be developed for angle crashes in Maryland. Instead, the study team applied the proportion of

angle crashes to the model for total crashes to obtain reasonable estimates of the expected number of angle crashes.

Additional variables were considered based on available data and included in the models if the following conditions were met:

- The variable significantly improved the model.

- The effect of the variable was intuitive (e.g., crashes increase as number of approaches increases).

Additional variables considered included:

- $\beta1$ = Area Type (urban/rural indicator) for Arkansas, Maryland, and Minnesota.

- $\beta2$ = Number of Intersection Legs for Arkansas, Maryland, and Minnesota.

- $\beta3$ = Type of Stop-Control (AWSC indicator) for Arkansas and Maryland.

- $\beta4$ = Illumination (presence of lighting indicator) for Maryland and Minnesota.

These variables entered the model form as adjustments to the base alpha value. The base alpha value was estimated for a particular baseline condition (i.e., rural, three-legged, one-way stop-control (OWSC) or two-way stop-control (TWSC), and no illumination). When the condition of the intersection is anything other than the baseline, an adjustment was applied to the base alpha value. The parameter values for $\beta1 - \beta4$ indicate the magnitude and direction of the adjustment to the base alpha value.

Yearly adjustment factors were also computed and applied as adjustments to the base alpha value similar to the $\beta1 - \beta4$ values. Again, a baseline condition (i.e., year) is assumed and the adjustment was applied to the base alpha value if the condition was anything but the baseline year.

In specifying a negative binomial error structure, the "dispersion" parameter, k, was iteratively estimated from the model and the data. The dispersion parameter relates the mean and variance of the SPF estimate and was used in equations 3 and 4 of the EB procedure. For a given dataset, smaller values of k indicate relatively better models.

The safety performance functions developed are presented in appendix A. Note the following in interpreting the output:

- The value of α is obtained as the $e^{(\alpha)}$, where α is from the model output.

- The value of the parameter k is used in the EB approach.

- The P-value gives the level at which the estimate is significant. For example, P-value = 0.05 indicates that the parameter estimate is statistically significant at the 5-percent level (or, alternatively, that the 95-percent confidence interval does not include a value of 0).

SPFs were estimated for the following crash classifications:

- Total (all severities and types combined).

- Injury (all fatal and injury crashes for all crash types combined).

- Right-angle (all severities combined).

- Rear-end (all severities combined).

RESULTS

Two sets of results were calculated. One set contains aggregate results for Arkansas and Maryland combined as well as for each State individually. The other set is based on a disaggregate analysis that attempted to discern factors that may be most favorable to installing STOP AHEAD pavement markings. The aggregate analysis provides evidence for the general effectiveness of the strategy, while the disaggregate analysis provides insight on the situations where the strategy may be most effective. The results focus on Arkansas and Maryland, while the Minnesota results are presented as supplementary. The Minnesota results are not combined with the other two States because crash rates at the strategy sites are relatively low in that State, and the installations were blanketed. A reduction in crashes is difficult to discern when the crash rate is already low, which may skew the results from the other States if included in the combined analysis. The results of the two analyses are presented in the following sections.

Aggregate Analysis

The main aggregate results (i.e., for Arkansas and Maryland) are shown in tables 7 through 9. The tables show the EB estimate of the crashes expected in the after period if the treatment had not been installed, the actual number of crashes in the after period, and two measures of change. The first measure of safety effect is the estimated percent reduction due to the strategy along with the standard error (S.E.) of this estimate; a negative value indicates an increase in crashes. If the magnitude of the percent change is at least 1.96 times higher than the standard error, then the change is statistically significant at the 95-percent confidence level; similarly, if the change is at least 1.64 times higher than the standard error, then the change is statistically significant at a confidence level of 90 percent. Those safety effects that are significant at the 95-percent confidence level are denoted by bold text. A negative sign indicates an increase in crashes. The second measure of safety effect is the change in the number of crashes per site year, which is calculated as the difference between the EB estimate of crashes expected in the after period and the count of observed crashes in the after period divided by the number of site-years in the after period.

Right-angle and rear-end crashes were selected as target crash types for this strategy. A separate analysis was completed for each of the target crash types to determine differential effects by crash type. A separate analysis was also completed for injury crashes (i.e., fatal plus all injury crashes) to determine the effects of this strategy on severity.

There is a statistically significant reduction in total crashes in both Arkansas, Maryland, and overall for the two States combined. For both right-angle crashes and rear-end crashes, the only significant change for the two main States was in Arkansas, for which the decreases in crashes

were statistically significant at the 95-percent confidence level for both crash types. For injury crashes, the crash reduction for the two States combined is statistically significant at the 90-percent confidence level.

The results for Minnesota are shown in table 10. As is evident, there are very few crashes at the strategy sites. Even so, these results support the conclusion from the evaluation of the other two States' implementations that this strategy is effective for reducing crashes. Please note the large standard errors for these results.

Table 7. Combined Results for 17 Arkansas and Maryland STOP AHEAD Sites.

	Right-Angle	Rear-End	Injury	Total
EB estimate of crashes expected in the after period without strategy	48.7	29.0	81.0	166.1
Count of crashes observed in the after period	51	21	64	115
Estimate of percent reduction	-3.6%	29.0%	21.6%	**31.1%**
Standard error	18.1	18.0	12.0	**8.0**
Estimate of reduction in crashes per site-year	-0.04	0.15	0.33	0.98

Note: A negative sign indicates an increase in crashes. Bold denotes those safety effects that are significant at the 95% confidence level.

Table 8. Results for Eight Arkansas STOP AHEAD Sites.

	Right-Angle	Rear-End	Injury	Total
EB estimate of crashes expected in the after period without strategy	22.1	10.0	25.9	47.7
Count of crashes observed in the after period	13	1	18	23
Estimate of percent reduction	**42.1%**	**90.3%**	31.7%	**52.3%**
Standard error	**17.5**	**9.5**	18.1	**10.8**
Estimate of reduction in crashes per site-year	0.43	0.42	0.37	1.15

Note: Bold denotes those safety effects that are significant at the 95% confidence level.

Table 9. Results for Nine Maryland STOP AHEAD Sites.

	Right-Angle	Rear-End	Injury	Total
EB estimate of crashes expected in the after period without strategy	26.6	19.0	55.1	118.3
Count of crashes observed in the after period	38	20	46	92
Estimate of percent reduction	-39.0%	-1.6%	17.6%	**22.9%**
Standard error	31.1	28.7	15.4	**10.5**
Estimate of reduction in crashes per site-year	-0.37	-0.03	0.30	0.86

Note: A negative sign indicates an increase in crashes. Bold denotes those safety effects that are significant at the 95% confidence level.

Table 10. Results for 158 Minnesota STOP AHEAD Sites.

	Right-Angle	Rear-End	Injury	Total
EB estimate of crashes expected in the after period without strategy	6.0	3.1	11.2	18.2
Count of crashes observed in the after period	2	1	2	12
Estimate of percent reduction	**66.9%**	**67.9%**	**82.2%**	34.1%
Standard error	**23.4**	**32.1**	**12.6**	19.3
Estimate of reduction in crashes per site-year	0.01	0.01	0.03	0.02

Note: Bold text denotes those safety effects that are significant at the 95% confidence level.

Disaggregate Analysis

A disaggregate analysis was completed to determine if safety effects are more or less pronounced for specific conditions. Right-angle and rear-end crashes are the primary targets of this measure and should properly be the basis for this analysis; however, there are too few of these crashes to facilitate a disaggregate analysis for these crash types. This analysis was completed for total crashes and injury crashes using only the combined results for Arkansas and Maryland for reasons explained earlier. Table 11 presents the results of the disaggregate analysis. Those safety effects that are significant at the 95-percent confidence level are denoted by bold text.

Table 11. Results of the Disaggregate Analysis for Arkansas and Maryland Combined.

Crash Type	Intersection Type	Sites	EB estimate of crashes expected in the after period without strategy	Count of crashes observed in the after period	Estimate of percent reduction (standard error)
Injury Crashes	Three-legged	5	19.3	9	**54.7% (16.4)**
	Four-legged	12	61.7	55	11.9% (15.0)
	AWSC	7	34.0	20	**42.3% (14.9)**
	OWSC/TWSC	10	47.0	44	7.7% (17.5)
Total Crashes	Three-legged	5	37.0	15	**60.1% (11.2)**
	Four-legged	12	129.1	100	**23.0% (9.9)**
	AWSC	7	71.7	32	**55.9% (9.1)**
	OWSC/TWSC	10	94.4	83	12.8% (12.2)

Note: Bold text denotes those safety effects that are significant at the 95% confidence level.

A disaggregate analysis could not be completed for area type (i.e., urban versus rural) because there were only two sites located in urban areas out of the total of 17 sites. Thus the results apply in general to rural sites, although the analysis was based on all 17 sites.

A consistent pattern emerges for both injury and total crashes when considering number of approaches (i.e., legs). The results indicate that installations at three-legged intersections are more effective than at four-legged intersections. For total crashes, the reductions for both three- and four-legged intersections are highly significant; however, the difference in effects is also significant.

The results were also disaggregated by stop-control, and there appears to be a difference between sites with AWSC and those with OWSC or TWSC. One-way stop-control corresponds to three-legged intersections where the stop-control is installed only on the minor approach. In this comparison, the stop-control is either on all approaches (i.e., AWSC) or not on all approaches (i.e., OWSC or TWSC). The results indicate that there is a reduction in total and injury crashes at both types of locations; however, the reductions are highly significant and relatively larger at AWSC intersections.

An attempt was made to discern the effects of installing STOP AHEAD markings for various AADT values. The AADT ranged from less than 1,000 to about 17,000 vehicles per day for Arkansas and Maryland. The disaggregate analysis revealed that there is a significant reduction in crashes for lower values of AADT; however, the magnitude of the reduction appears to decrease and becomes insignificant as AADT values increase. However, these indications are too weak to support a definitive conclusion on the impact of AADT.

There are advantages and disadvantages to applying the results from the disaggregate analysis. The disaggregate analysis can shed light on specific conditions where strategies may be most effective; however, disaggregate analyses are, by nature, based on smaller sample sizes than aggregate analyses. Smaller samples lead to larger confidence intervals and less precise results. One cannot apply a general rule to using either the aggregate or disaggregate analysis, but rather, this should be based on a case-by-case basis. In the case of the STOP AHEAD analysis, the aggregate analysis provides support for the use of this strategy (i.e., STOP AHEAD pavement markings are associated with a general reduction in crashes). The disaggregate analysis indicates specific conditions that should be given priority due to the relative effectiveness of this strategy (three-legged and AWSC locations).

A discussion of the differential effects is undertaken in the conclusions section. It should be noted, however, that further investigation was undertaken to ensure that the effects were not due to biases in the analysis. This further investigation involved an examination of the results of a naïve before-after study that compared crash frequencies pre- and post-strategy and did not use safety performance functions. The naïve before-after study yielded similar conclusions to the EB study regarding the influence of the number of approaches, although the magnitudes of the crash effects were different than those in table 11. These results apply in general to rural intersections, since there were too few urban sites available for the disaggregate analysis.

ECONOMIC ANALYSIS

The purpose of the economic analysis was to evaluate the economic feasibility of STOP AHEAD pavement markings. The economic analysis was accomplished by estimating the life cycle cost of the strategy and the discounted annual cost of the strategy. Crash costs were estimated from the most recent FHWA unit crash cost data for unsignalized intersections. The annual benefits of the strategy, necessary to offset the cost, were estimated by comparing the cost of the strategy to the crash costs. Finally, the results from the aggregate and disaggregate crash analyses were compared to the economic analysis to determine the expected economic feasibility.

Arkansas, Maryland, and Minnesota provided data regarding the installation and maintenance costs of STOP AHEAD pavement markings as well as the expected service life. There were two types of pavement markings identified: latex paint with glass beads and thermoplastic material. The two types of installations differ by cost and service life; the thermoplastic lasts longer but is

more expensive to install. Due to the differences in installation cost and service life, separate economic analyses are performed for the latex and thermoplastic pavement markings. Based on the information provided by the States, a conservative estimate for the cost of STOP AHEAD pavement markings is $140 for latex and $1,500 for thermoplastic per approach leg. The cost includes materials, equipment, and labor. The expected service life for the STOP AHEAD pavement markings is two years for the latex and five years for the thermoplastic. The formula to calculate annual cost is:

$$\text{Annual Cost} = \frac{C * R}{1 - (1 + R)^{-N}}$$

(8)

Where:

C	is the installation cost.
R	is the discount rate.
N	is the expected service life (years).

Based on the Office of Management and Budget, a discount rate of seven percent was used to determine the annual cost of the strategy. This resulted in an annual cost of $78 per approach for latex and $366 per approach for thermoplastic, which requires a $156 and $732 annual savings in crash costs per installation, respectively, to achieve a 2:1 benefit-cost ratio.

The most recent FHWA mean comprehensive cost per crash for unsignalized intersections[12] is $55,060 for an undefined collision based on 2001 dollar values. Comprehensive crash costs represent the present value, computed at a discount rate, of all costs over the victim's expected life span that result from a crash. The major categories of costs used in the calculation of comprehensive crash costs include medical-related costs, emergency services, property damage, lost productivity, and monetized quality-adjusted life years.[12] The value of an undefined crash is based on the comprehensive crash costs of various crash types and the proportion of each type of crash. The necessary savings to achieve a 2:1 benefit-cost ratio would require a reduction in total crashes of 0.006 crashes per intersection-year for the latex application, assuming a TWSC with installations on both approaches. The corresponding number for the thermoplastic application is 0.027 crashes per intersection-year, assuming a TWSC installation. The necessary reductions per intersection-year would, however, change for an AWSC intersection because the pavement markings would be installed on all approaches. The necessary savings would now require a reduction of 0.011 total crashes per intersection-year for the latex application, while thermoplastic installations would require a reduction of 0.053 crashes per intersection-year. Based on the results in tables 7 through 9, it seems that the necessary reductions are easily achievable. The benefits will be less pronounced for intersections with relatively low crash rates. For example, the crash rate is 0.04 crashes per intersection-year for the Minnesota strategy sites in the before period (table 10). While there is a realized benefit after installing STOP AHEAD pavement markings, a reduction of 0.05 crashes per intersection-year is not possible to achieve a 2:1 benefit-cost ratio for thermoplastic installations at AWSC locations.

SUMMARY

The objective of this study was to evaluate the safety effectiveness of STOP AHEAD pavement markings at unsignalized intersections as measured by crash frequency. The study also examined the effects of STOP AHEAD markings on specific crash types and for different intersection configurations (e.g., three-legged/four-legged).

The results of the aggregate analysis indicate a statistically significant reduction in total crashes for Arkansas, Maryland, and overall for the two States combined. For both right-angle and rear-end crashes, the only significant change for the two States is in Arkansas, for which there is a statistically significant reduction in both crash types at the 95-percent confidence level. The aggregate analysis in Arkansas and Maryland indicates that STOP AHEAD pavement markings may significantly reduce total crashes at unsignalized intersections. The results for Minnesota support the conclusion from the evaluation of the other two States' implementations that this strategy is effective for reducing crashes.

The disaggregate analysis provided further insight into the circumstances where crash reductions were identified. Installations at three-legged intersections were found to be more effective than at four-legged intersections. The analysis also indicates a highly significant reduction in injury and total crashes for AWSC intersections. The effectiveness of STOP AHEAD pavement markings also appeared to vary by AADT, but these indications are based on too small of a sample size to support a definitive conclusion on the impact of AADT.

CONCLUSION

The general conclusion from this research is that a reduction in crashes can be expected with the installation of STOP AHEAD pavement markings. The results are consistent between Arkansas and Maryland, which are combined in the main analysis. Minnesota was not included in the main analysis because of the relatively low crash rates at the STOP AHEAD sites; however, the results support those from Arkansas and Maryland.

From a practical standpoint, the aggregate analysis supports the conclusion that a total crash reduction of at least 15 percent can be expected with the installation of STOP AHEAD pavement markings as presented in table 12. This conclusion is based on the conservative lower 95-percent confidence limit from the combined aggregate analysis of STOP AHEAD pavement markings in Arkansas and Maryland. The lower 95-percent confidence limit is suggested because the analysis is based on a limited number of sites that were treated for a specific reason (i.e., perceived safety problem). However, it may be necessary to use the point estimate (31-percent reduction) when comparing various potential countermeasures, particularly when confidence limits are not available for all potential strategies. This way, all countermeasures are treated equally when making a cost-benefit comparison.

Table 12. Expected Crash Reductions for Installations of STOP AHEAD Pavement Markings.

Crash Type	Point Estimate	Standard Error	Conservative Estimate
Total Crashes	31.1%	8.0	**15.4%**

Note: The conservative estimate is based on the lower 95% confidence interval and is calculated as the point estimate minus 1.96 times the standard error.

It is likely that STOP AHEAD pavement markings will be most effective at locations with a high frequency of target collisions (i.e., right-angle and rear-end), particularly where driver awareness may be an issue. The disaggregate analysis supports that the reduction may not be consistent across intersection types and provides evidence for those locations where this strategy may be most effective. Specifically, crash reductions are expected to be greatest at three-legged and AWSC intersections. The disaggregate analysis may be used to prioritize locations for treatment; however, the estimated percent reductions from the disaggregate analysis should not be applied directly because of the limited sample sizes.

Given the low-cost of this strategy, even with the conservative assumptions, a modest reduction in crashes is needed to justify their use. Based on the evidence provided by the estimated safety effectiveness of STOP AHEAD pavement markings, the necessary reduction to obtain a 2:1 benefit-cost ratio is easily achieved. Therefore, this strategy has the potential to reduce crashes cost-effectively, particularly at three-legged and AWSC intersections with a high crash frequency.

APPENDIX A: ARKANSAS SAFETY PERFORMANCE FUNCTIONS (SPFS)

Table 13. Arkansas Total Crashes—All Severities.

Parameter	Estimate	Standard Error	P-value
α (1994, rural)	-9.4296	0.8124	0.0000
Y1 (Adjustment to α if 1995)	-0.0650	0.2332	0.7810
Y2 (Adjustment to α if 1996)	0.0817	0.2273	0.7190
Y3 (Adjustment to α if 1997)	-0.0977	0.2333	0.6750
Y4 (Adjustment to α if 1998)	0.1201	0.2271	0.5970
Y5 (Adjustment to α if 1999)	0.2206	0.2243	0.3250
Y6 (Adjustment to α if 2000)	0.2271	0.2235	0.3090
Y7 (Adjustment to α if 2001)	0.2875	0.2210	0.1930
Y8 (Adjustment to α if 2002)	0.1237	0.2232	0.5790
Y9 (Adjustment to α if 2003)	0.1686	0.2225	0.4490
Y10 (Adjustment to α if 2004)	0.5092	0.2165	0.0190
β0 (ln[ADT])	1.1033	0.0916	0.0000
β1 (Adjustment to α if Urban)	1.6402	0.2677	0.0000
k	0.6572	0.0816	0.0000

Note: A negative sign indicates an increase in crashes.

Table 14. Arkansas Injury Crashes.

Parameter	Estimate	Standard Error	P-value
α (1994, rural)	-10.6141	1.0889	0.0000
Y1 (Adjustment to α if 1995)	-0.0331	0.2994	0.9120
Y2 (Adjustment to α if 1996)	0.1313	0.2891	0.6500
Y3 (Adjustment to α if 1997)	-0.3576	0.3131	0.2530
Y4 (Adjustment to α if 1998)	0.2232	0.2839	0.4320
Y5 (Adjustment to α if 1999)	-0.1145	0.2965	0.6990
Y6 (Adjustment to α if 2000)	0.1850	0.2845	0.5150
Y7 (Adjustment to α if 2001)	0.2948	0.2805	0.2930
Y8 (Adjustment to α if 2002)	0.0699	0.2859	0.8070
Y9 (Adjustment to α if 2003)	0.0617	0.2834	0.8280
Y10 (Adjustment to α if 2004)	0.7120	0.2656	0.0070
$\beta 0$ (ln[ADT])	1.1429	0.1223	0.0000
$\beta 1$ (Adjustment to α if Urban)	1.6277	0.2834	0.0000
k	0.6225	0.1313	0.0000

Note: A negative sign indicates an increase in crashes.

Table 15. Arkansas Right-Angle Crashes.

Parameter	Estimate	Standard Error	P-value
α (1994, rural)	-12.1081	1.2381	0.0000
Y1 (Adjustment to α if 1995)	-0.4701	0.3371	0.1630
Y2 (Adjustment to α if 1996)	0.0223	0.3077	0.9420
Y3 (Adjustment to α if 1997)	-0.4780	0.3405	0.1600
Y4 (Adjustment to α if 1998)	-0.3900	0.3239	0.2290
Y5 (Adjustment to α if 1999)	-0.0598	0.3074	0.8460
Y6 (Adjustment to α if 2000)	0.0178	0.3024	0.9530
Y7 (Adjustment to α if 2001)	0.5069	0.2872	0.0780
Y8 (Adjustment to α if 2002)	-0.2868	0.3157	0.3640
Y9 (Adjustment to α if 2003)	-0.2342	0.3104	0.4510
Y10 (Adjustment to α if 2004)	0.4699	0.2851	0.0990
$\beta 0$ (ln[ADT])	1.3052	0.1391	0.0000
$\beta 1$ (Adjustment to α if Urban)	1.9792	0.2941	0.0000
k	0.6780	0.1550	0.0000

Note: A negative sign indicates an increase in crashes.

Table 16. Arkansas Rear-End Crashes.

Parameter	Estimate	Standard Error	P-value
α (1994, rural, TWSC)	-15.2446	1.4582	0.0000
Y1 (Adjustment to α if 1995)	0.0466	0.3887	0.9050
Y2 (Adjustment to α if 1996)	-0.1353	0.4011	0.7360
Y3 (Adjustment to α if 1997)	0.1076	0.3848	0.7800
Y4 (Adjustment to α if 1998)	0.5355	0.3671	0.1450
Y5 (Adjustment to α if 1999)	0.2633	0.3736	0.4810
Y6 (Adjustment to α if 2000)	0.0137	0.3878	0.9720
Y7 (Adjustment to α if 2001)	0.4059	0.3629	0.2630
Y8 (Adjustment to α if 2002)	0.5257	0.3566	0.1400
Y9 (Adjustment to α if 2003)	0.3042	0.3622	0.4010
Y10 (Adjustment to α if 2004)	0.4447	0.3600	0.2170
$\beta 0$ (ln[ADT])	1.6199	0.1620	0.0000
$\beta 1$ (Adjustment to α if Urban)	1.4847	0.3644	0.0000
$\beta 3$ (Adjustment to α if AWSC)	-0.6622	0.2311	0.0040
k	1.1275	0.2299	0.0000

Note: A negative sign indicates an increase in crashes.

Maryland SPFs for Sites Without Minor ADT

Table 17. Maryland Total Crashes for Sites Without Minor ADT—All Severities.

Parameter	Estimate	Standard Error	P-value
α (1996, rural)	-2.0105	0.6476	0.0020
Y1 (Adjustment to α if 1997)	-0.0734	0.1994	0.7130
Y2 (Adjustment to α if 1998)	-0.0550	0.1976	0.7810
Y3 (Adjustment to α if 1999)	-0.1438	0.2004	0.4730
Y4 (Adjustment to α if 2000)	0.0318	0.1959	0.8710
Y5 (Adjustment to α if 2001)	-0.0158	0.1974	0.9360
Y6 (Adjustment to α if 2002)	0.0986	0.1942	0.6120
Y7 (Adjustment to α if 2003)	0.2122	0.1926	0.2700
Y8 (Adjustment to α if 2004)	0.0981	0.1960	0.6170
Y9 (Adjustment to α if 2005)	-0.1557	0.2006	0.4380
β0 (ln[ADT])	0.2518	0.0715	0.0000
β1 (Adjustment to α if Urban)	0.6318	0.0925	0.0000
k	0.5036	0.0712	0.0000

Note: A negative sign indicates an increase in crashes.

Table 18. Maryland Injury Crashes for Sites Without Minor ADT.

Parameter	Estimate	Standard Error	P-value
α (1996, rural)	-3.1259	0.8251	0.0000
Y1 (Adjustment to α if 1997)	0.0345	0.2495	0.8900
Y2 (Adjustment to α if 1998)	0.0115	0.2493	0.9630
Y3 (Adjustment to α if 1999)	-0.1359	0.2561	0.5960
Y4 (Adjustment to α if 2000)	-0.0190	0.2507	0.9400
Y5 (Adjustment to α if 2001)	-0.0585	0.2512	0.8160
Y6 (Adjustment to α if 2002)	-0.0798	0.2534	0.7530
Y7 (Adjustment to α if 2003)	0.1947	0.2423	0.4220
Y8 (Adjustment to α if 2004)	0.2299	0.2415	0.3410
Y9 (Adjustment to α if 2005)	0.0137	0.2483	0.9560
$\beta0$ (ln[ADT])	0.2872	0.0907	0.0020
$\beta1$ (Adjustment to α if Urban)	0.5644	0.1177	0.0000
k	0.4610	0.1136	0.0000

Note: A negative sign indicates an increase in crashes.

Table 19. Maryland Right-Angle Crashes for Sites Without Minor ADT.

No model was developed for right-angle crashes. Estimates were based on the total crash model and the proportion of right-angle crashes (16 percent).

Table 20. Maryland Rear-End Crashes for Sites Without Minor ADT.

Parameter	Estimate	Standard Error	P-value
α (1996, rural)	-10.0794	1.2696	0.0000
Y1 (Adjustment to α if 1997)	0.5123	0.3749	0.1720
Y2 (Adjustment to α if 1998)	0.4021	0.3743	0.2830
Y3 (Adjustment to α if 1999)	0.4464	0.3750	0.2340
Y4 (Adjustment to α if 2000)	0.1995	0.3843	0.6040
Y5 (Adjustment to α if 2001)	0.3343	0.3749	0.3730
Y6 (Adjustment to α if 2002)	0.5347	0.3644	0.1420
Y7 (Adjustment to α if 2003)	0.6549	0.3594	0.0680
Y8 (Adjustment to α if 2004)	0.6716	0.3595	0.0620
Y9 (Adjustment to α if 2005)	0.3238	0.3715	0.3830
β0 (ln[ADT])	0.9380	0.1360	0.0000
β1 (Adjustment to α if Urban)	0.3801	0.1624	0.0190
k	0.7992	0.2080	0.0000

Note: A negative sign indicates an increase in crashes.

Maryland SPFs for Sites with Major and Minor ADT

Table 21. Maryland Total Crashes for Sites with Major and Minor ADT—All Severities.

Parameter	Estimate	Standard Error	P-value
α (1996, rural)	-2.2367	0.9728	0.0210
Y1 (Adjustment to α if 1997)	-0.3098	0.2506	0.2160
Y2 (Adjustment to α if 1998)	-0.1125	0.2440	0.6450
Y3 (Adjustment to α if 1999)	-0.1531	0.2460	0.5340
Y4 (Adjustment to α if 2000)	-0.0214	0.2428	0.9300
Y5 (Adjustment to α if 2001)	-0.0323	0.2442	0.8950
Y6 (Adjustment to α if 2002)	0.0140	0.2415	0.9540
Y7 (Adjustment to α if 2003)	0.0496	0.2421	0.8380
Y8 (Adjustment to α if 2004)	-0.2362	0.2495	0.3440
Y9 (Adjustment to α if 2005)	-0.2295	0.2487	0.3560
β0 (ln[Major ADT])	0.2804	0.1058	0.0080
β1 (Adjustment to α if Urban)	0.6470	0.1303	0.0000
k	0.5996	0.0924	0.0000

Note: A negative sign indicates an increase in crashes.

Table 22. Mcaryland Injury Crashes for Sites with Major and Minor ADT.

Parameter	Estimate	Standard Error	P-value
α (1996, rural)	-3.7839	1.1851	0.0010
Y1 (Adjustment to α if 1997)	-0.2108	0.2963	0.4770
Y2 (Adjustment to α if 1998)	-0.1120	0.2896	0.6990
Y3 (Adjustment to α if 1999)	-0.1698	0.2930	0.5620
Y4 (Adjustment to α if 2000)	-0.2886	0.2984	0.3330
Y5 (Adjustment to α if 2001)	-0.1599	0.2901	0.5820
Y6 (Adjustment to α if 2002)	-0.4073	0.3040	0.1800
Y7 (Adjustment to α if 2003)	-0.0634	0.2877	0.8260
Y8 (Adjustment to α if 2004)	-0.1150	0.2903	0.6920
Y9 (Adjustment to α if 2005)	-0.1077	0.2889	0.7090
β0 (ln[Major ADT])	0.3552	0.1285	0.0060
β1 (Adjustment to α if Urban)	0.7096	0.1690	0.0000
k	0.4732	0.1311	0.0000

Note: A negative sign indicates an increase in crashes.

Table 23. Maryland Right-Angle Crashes for Sites with Major and Minor ADT.

No model was developed for right-angle crashes. Estimates were based on the total crash model and the proportion of right-angle crashes (24 percent).

Table 24. Maryland Rear-End Crashes for Sites with Major and Minor ADT.

Parameter	Estimate	Standard Error	P-value
α (1996, rural)	-13.1856	1.7607	0.0000
Y1 (Adjustment to α if 1997)	0.3556	0.4600	0.4400
Y2 (Adjustment to α if 1998)	0.4919	0.4454	0.2690
Y3 (Adjustment to α if 1999)	0.7169	0.4408	0.1040
Y4 (Adjustment to α if 2000)	0.2050	0.4591	0.6550
Y5 (Adjustment to α if 2001)	0.4715	0.4406	0.2850
Y6 (Adjustment to α if 2002)	0.6554	0.4313	0.1290
Y7 (Adjustment to α if 2003)	0.4898	0.4361	0.2610
Y8 (Adjustment to α if 2004)	0.3676	0.4409	0.4040
Y9 (Adjustment to α if 2005)	0.1096	0.4520	0.8080
$\beta 0$ (ln[ADT])	1.2793	0.1808	0.0000
k	0.9095	0.2523	0.0000

Note: A negative sign indicates an increase in crashes.

Table 25. Minnesota Total Crashes—All Severities.

Parameter	Estimate	Standard Error	P-value
α (1995, 3-legged)	-5.1601	0.8289	0.0000
Y1 (Adjustment to α if 1996)	-0.1507	0.2527	0.5510
Y2 (Adjustment to α if 1997)	-0.2488	0.2543	0.3280
Y3 (Adjustment to α if 1998)	-0.1049	0.2506	0.6760
Y4 (Adjustment to α if 1999)	0.1603	0.2429	0.5090
Y5 (Adjustment to α if 2000)	-0.1293	0.2505	0.6060
Y6 (Adjustment to α if 2001)	0.0066	0.2475	0.9790
Y7 (Adjustment to α if 2002)	-0.2160	0.2541	0.3950
Y8 (Adjustment to α if 2003)	0.0960	0.2447	0.6950
Y9 (Adjustment to α if 2004)	0.2231	0.2415	0.3560
Y10 (Adjustment to α if 2005)	-0.0348	0.2490	0.8890
β0 (ln[ADT])	0.2036	0.0813	0.0120
β2 (Adjustment to α if 4-legged)	0.4713	0.1253	0.0000
k	6.4111	0.5724	0.0000

Note: A negative sign indicates an increase in crashes.

Table 26. Minnesota Injury Crashes.

Parameter	Estimate	Standard Error	P-value
α (1995, 3-legged)	-5.9646	1.1390	0.0000
Y1 (Adjustment to α if 1996)	-0.4510	0.3707	0.2240
Y2 (Adjustment to α if 1997)	-0.2317	0.3523	0.5110
Y3 (Adjustment to α if 1998)	-0.1613	0.3494	0.6440
Y4 (Adjustment to α if 1999)	0.2495	0.3271	0.4460
Y5 (Adjustment to α if 2000)	-0.3137	0.3584	0.3810
Y6 (Adjustment to α if 2001)	-0.2230	0.3522	0.5270
Y7 (Adjustment to α if 2002)	-0.0200	0.3425	0.9540
Y8 (Adjustment to α if 2003)	0.0189	0.3384	0.9560
Y9 (Adjustment to α if 2004)	0.3008	0.3255	0.3550
Y10 (Adjustment to α if 2005)	-0.0693	0.3455	0.8410
β0 (ln[ADT])	0.2091	0.1125	0.0630
β2 (Adjustment to α if 4-legged)	0.4157	0.1772	0.0190
k	7.9519	1.3149	0.0000

Note: A negative sign indicates an increase in crashes.

Table 27. Minnesota Right-Angle Crashes.

Parameter	Estimate	Standard Error	P-value
α (1995, three-legged)	-10.7648	1.4473	0.0000
Y1 (Adjustment to α if 1996)	-0.6118	0.3962	0.1230
Y2 (Adjustment to α if 1997)	-0.2637	0.3641	0.4690
Y3 (Adjustment to α if 1998)	-0.4176	0.3800	0.2720
Y4 (Adjustment to α if 1999)	0.2970	0.3371	0.3780
Y5 (Adjustment to α if 2000)	-0.0096	0.3487	0.9780
Y6 (Adjustment to α if 2001)	-0.1343	0.3627	0.7110
Y7 (Adjustment to α if 2002)	-0.3647	0.3711	0.3260
Y8 (Adjustment to α if 2003)	-0.0144	0.3524	0.9670
Y9 (Adjustment to α if 2004)	0.0631	0.3494	0.8570
Y10 (Adjustment to α if 2005)	-0.3170	0.3686	0.3900
$\beta0$ (ln[ADT])	0.2055	0.1189	0.0840
$\beta2$ (Adjustment to α if four-legged)	1.6573	0.2638	0.0000
k	7.9844	1.3697	0.0000

Note: A negative sign indicates an increase in crashes.

Table 28. Minnesota Rear-End Crashes.

Parameter	Estimate	Standard Error	P-Value
α (1995)	-5.6226	1.1892	0.0000
Y1 (Adjustment to α if 1996)	0.4189	0.4551	0.3570
Y2 (Adjustment to α if 1997)	-0.2165	0.5153	0.6740
Y3 (Adjustment to α if 1998)	0.4614	0.4503	0.3060
Y4 (Adjustment to α if 1999)	0.5118	0.4462	0.2510
Y5 (Adjustment to α if 2000)	-0.2403	0.5151	0.6410
Y6 (Adjustment to α if 2001)	0.3159	0.4602	0.4920
Y7 (Adjustment to α if 2002)	0.2494	0.4661	0.5930
Y8 (Adjustment to α if 2003)	-0.1238	0.5015	0.8050
Y9 (Adjustment to α if 2004)	0.2330	0.4664	0.6170
Y10 (Adjustment to α if 2005)	0.1552	0.4732	0.7430
β0 (ln[ADT])	0.2370	0.1381	0.0860
k	7.8007	2.3437	0.0000

Note: A negative sign indicates an increase in crashes.

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