All-Weather Pavement Marking for Work Zones: Field Evaluation in North Carolina and Ohio

Temporary Wet-Weather Pavement Markings for Work Zones, Phase II Final Report

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16. Abstract

To address the problem of seemingly invisible pavement markings under nighttime, rainy conditions, 3M developed “All-Weather Paint” (AWP), which uses highly retroreflective elements in combination with latex-based pavement marking installed by highway agencies. Whereas standard pavement markings using waterborne pavement marking and glass beads become harder to see in the rain, the AWP performed well during closed-circuit field tests.

Researchers at North Carolina State University and Ohio University teamed up to conduct tests in active highway work zones. The team defined four measures of effectiveness (MOE) in an attempt to quantify safety performance when comparing the AWP to standard pavement marking materials under real-world driving conditions: retroreflectivity, vehicle travel speed, rate of lane encroachments, and linear lane displacement. Data collection procedures for each MOE are systematically outlined throughout the report.

From the results, the study concluded the following: (1) Retroreflectivity values were confirmed to be higher for AWP when compared to standard pavement markings. However, the AWP retroreflectivity values were inconsistent, likely because of the variation of application methods by pavement marking contractors. (2) Speed was used as a surrogate MOE to evaluate safety performance. It was not clear if an increase or decrease in speed has a positive effect on safety. Results showed that speed generally increased as drivers exited work zone lane shifts for all marking types; however, no consistent finding was noted between the two marking systems in similar curves. (3) The findings for lane encroachments varied throughout the sites. While the first site studied indicated that more lane encroachments occurred at standard pavement marking crossovers, a more robust study at a second site found the results to be statistically insignificant. (4) When assessing lateral lane placement, researchers found statistically significant but varied results. More often than not, motorists maintain safer lane placements when traveling along the AWP delineated lanes.

This report documents Phase II of this project. The Phase I report is available on the FHWA website at: http://www.fhwa.dot.gov/hfl/partnerships/3m/phase1/index.cfm.

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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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LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
ANOVA	Analysis of Variance
AWP	All-Weather Paint
CCTV	Closed-Circuit Television
DOT	Department of Transportation
FHWA	Federal Highway Administration
LIDAR	Light Detection and Ranging
MOE	Measure of Effectiveness
NOAA	National Oceanic and Atmospheric Administration
RI	Refractive Index
RPM	Raised Pavement Marker
TIP	Transportation Improvement Project

EXECUTIVE SUMMARY

Traffic crashes cause tens of thousands of deaths every year; thus, highway safety is at the forefront of the decision making process of transportation improvement projects. Traffic-related fatalities and severe crashes top the list and are immediate areas of concern to transportation policy and decision makers. Aside from mistakes made by drivers, the conditions of the road and environment often factor in the motorist decision process. Factors including, but not limited to, weather, lighting, and surface deterioration are examples often considered in the condition of the national highway system. Pavement markings are the focus of this research effort—specifically, improving their retroreflectivity under nighttime rainy conditions, which often hinder motorists' ability to drive safely, especially in work zones, where quick decisions are often a life-or-death situation. Decreased visibility of lane delineation and lack of situational awareness make navigation through complex work zones potentially unsafe for drivers.

To address the problem of poor visibility of pavement markings under nighttime, rainy conditions, 3M developed "All-Weather Paint" (AWP). AWP utilizes highly retroreflective elements in combination with latex-based pavement marking installed by highway agencies. Whereas standard pavement markings become harder to see in the rain, the AWP performed well during closed-circuit field tests.

Researchers at North Carolina State University and Ohio University teamed up to conduct tests in active highway work zones. Five test sites were selected in North Carolina and Ohio. The team defined four measures of effectiveness (MOE) in an attempt to quantify safety performance when comparing the AWP to standard pavement marking under real-world driving conditions: pavement marking retroreflectivity, vehicle travel speed, rate of lane encroachments, and linear lane displacement. Data collection procedures for each MOE are systematically outlined throughout the report. Basic statistical analyses were performed, and the methodologies are stated herein.

From the results, the study concluded the following:

- Retroreflectivity values were confirmed to be higher for AWP when compared to standard pavement markings. However, the AWP retroreflectivity values were inconsistent, which was likely due to the variation of application methods by pavement marking contractors.

- Speed was used as a surrogate MOE to evaluate safety performance. It was not clear if an increase or decrease in speed has a positive effect on safety. Results showed that speed generally increased as drivers exited work zone lane shifts for all pavement marking types; however, no consistent finding was noted between the two marking types in similar curves.

- The findings for lane encroachments varied throughout the sites. While the first site studied indicated that more lane encroachments occurred at standard pavement marking crossovers, the more robust study of the second site found results to be statistically insignificant.

- Finally, when assessing lateral lane placement, researchers found statistically significant but varied results. More often than not, motorists maintain safer lane placements when traveling along the AWP delineated lanes.

In summary, this study shows that AWP provides a low-cost, all-weather marking to improve lane visibility and to enhance safety.

INTRODUCTION

Pavement markings are a vital tool for safely navigating our nation's roads. Pavement markings come in many variations, depending on the application. Many of the pavement markings used today are especially difficult to see in the rain, particularly during nighttime hours. One commonly used pavement marking (herein referred to as "standard pavement marking") uses a latex paint coupled with 1.5 refractive index glass beads that retroreflect light back to the driver. More times than not, this application method is used in temporary installations such as work zones. However, because the marking is hard to see during nighttime rainy conditions, there is concern that drivers may have lane-keeping issues when navigating through active work zones. This poses a hazard to drivers and increases the risk of crashes. Therefore, most States currently supplement the pavement marking application with raised pavement markers to provide a visual cue to the driver on the location of the lane line.

Funded under the Federal Highway Administration (FHWA) "Highways for LIFE" technology partnerships program, this research project aims to test a variation of the latex-based pavement marking that uses specially designed optical elements for temporary applications such as work zones. Developed by 3M, the "All-Weather Pavement marking" (AWP) consists of a standard pavement marking supplemented with additional optical elements that retroreflect light in rain conditions, greatly increasing visibility during rain events.

Phase I of this study involved testing in a controlled environment. First, 24 pavement marking samples were installed on a test deck in New Orleans, LA, and time-series data regarding their retained retroreflective properties were collected. Three prototype all-weathering markings were identified to carry into the next task, which involved the installation of the pavement markings at the Texas Transportation Institute rain range. In these studies, the AWP and conventional markings demonstrated substantial differences in retroreflectivity; however, these studies were not conducted under real-world driving conditions, and they could not address any issues with contractors applying the markings in a dynamic environment where application time must be considered to keep traffic moving.

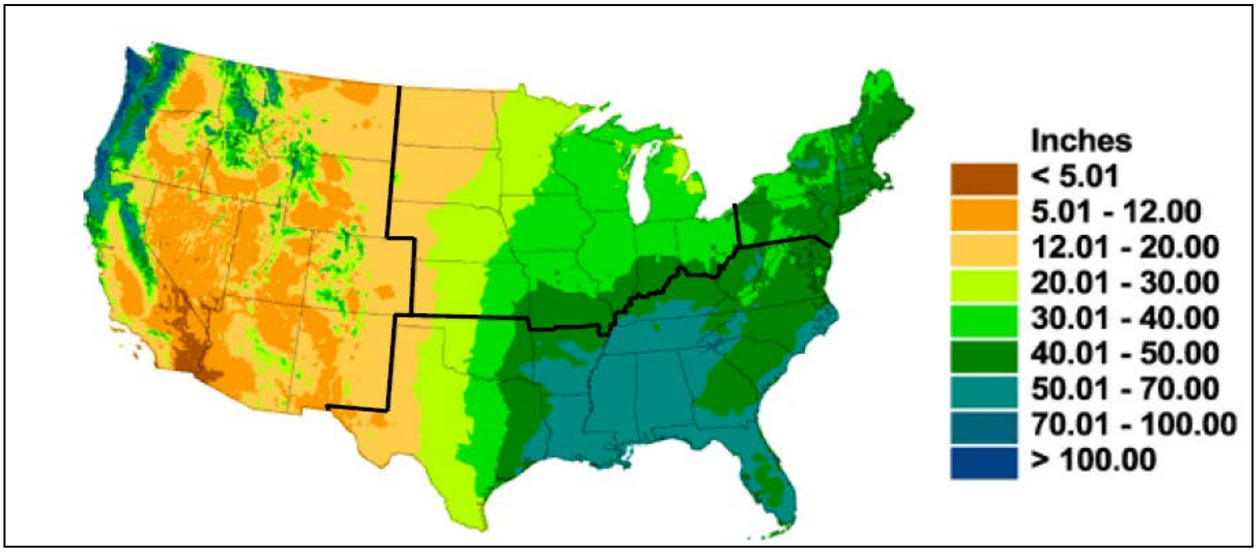
To build on the findings of Phase I, the Phase II effort aims to study actual drivers as they navigate through work zones by comparing standard pavement marking to the AWP under daytime, nighttime, and rainy conditions. First, the research team conducted a literature review to learn from previous research in the area of pavement marking studies. Following this effort, they selected field test sites based on a variety of factors, including a minimum of two lanes per direction in the transition zone, no raised pavement markers (RPMs), a minimum speed limit of 45 miles per hour, and no disruption from nearby traffic signals. In total, five sites were chosen, three in North Carolina and two in Ohio. Next, standard pavement marking and the AWP were applied in each of the chosen work zones. The analysis considered four measures of effectiveness (MOE): retroreflectivity, speeds, lane encroachments, and lateral lane placement. Retroreflectivity was utilized to determine differences in pavement marking application across sites and between pavement marking types at the same site. Speed was used to supplement findings from the latter two MOEs since higher or lower speeds could not be correlated to better or worse driving conditions. Last, lane encroachment and lateral lane placement were the primary MOEs used to determine if safety had improved using the new AWP.

LITERATURE REVIEW

To gain more insight into the part that pavement markings play in roadway safety, the researchers conducted a literature review at the start of Phase II of the study. This chapter details previous findings regarding adverse weather crashes, work zone safety, and pavement marking effectiveness. This information provided valuable direction for the conduct of Phase II.

RAIN AND NIGHT CONDITIONS NATIONWIDE

Rainfall frequency across the United States varies greatly, and it creates more opportunities for difficult driving conditions for certain areas. Higher rainfall means an increased exposure to wet driving surfaces. In 2008, Pisano, Goodwin, and Rossetti gathered adverse weather crash data and related it to weather conditions across the country.[(1)] Their report included a nationwide rainfall map, shown in figure 1. From a rainfall frequency perspective, it is clear that drivers in the northwestern and southeastern United States are at a higher risk due to higher rainfall.



1 inch = 25.4 mm

Figure 1. Chart. 2008 mean total precipitation.[(1)]

Nighttime driving conditions also vary over parts of the U.S. In the northern parts of the continental U.S., nighttime can last over 15 hours, and drivers are forced to operate their vehicles in dark conditions, including during peak travel periods. This is the case in such cities as Seattle, Washington; Minneapolis, Minnesota; and Rochester, New York. Even in the southernmost urban areas such as Miami, Florida, and Corpus Christi, Texas, wintertime nights are around 13.5 hours.[(2)]

ADVERSE WEATHER CRASHES

Driving in rainy, snowy, sleety, and/or windy conditions carries additional risk above that of driving in dry conditions. Both a driver's perception of the road ahead and the wheel's ability to grip the road are reduced, making it more difficult to maneuver safely on highways. Between 1995 and 2005, 24 percent of all traffic fatalities were due to adverse weather, about 7,400 each year. The number injured annually in adverse weather crashes is a couple of magnitudes larger, totaling 673,000.[(1)] When further examining the statistics, 47 percent of these crashes occurred during rainfall, and 75 percent occurred on wet pavement. The remainder are caused by snowy and slushy roads, fog, and high winds.

The Midwest has the highest rate of average weather-related crashes because of high amounts of snowfall. In fact, 40 percent of all nationwide weather-related crashes occur in this area, which only accounts for 22 percent of the U.S. population. The South, however, is not far behind, with 32 percent of total weather-related crashes and 36 percent of the total U.S. population. The ratio of rainfall-related crashes in the South is the highest in the nation—over 64 percent of all weather-related crashes, which likely corresponds to the high levels of rainfall.

Compared to the growth in vehicle miles traveled, adverse weather-related crashes decreased during the study period. Regardless, the average number of crashes is over 1.5 million annually. The risk of driving in adverse weather will remain high due to low visibility during precipitation and poor tire traction on wet pavement, which consequently reduces vehicle control and maneuverability.

Qiu and Nixon conducted a study to compile the research done on the effects of adverse weather on crash rates, injury crash rates, and fatal crash rates. Through meta-analysis, they compared daily cash rates during adverse weather with those during non-adverse weather. At a confidence interval of 95 percent, the study concluded that rain could increase the crash rate by 71 percent and the injury rate by 49 percent.[3] Although the percentage of crash rates related to snow events has decreased over time, the study found that this was not the case for crash rates related to rain events. The increased risk of crashes, injuries, and fatalities during rainy and/or wet conditions demonstrates the need for more informative, noticeable pavement markings.

Hummer et al. analyzed data from the Highway Safety Information System to document the characteristics of crashes in North Carolina.[4] They found that, from 2003 to 2005, approximately one-third of crashes occurred in reduced lighting conditions (dusk, dawn, or dark). Additionally, 23 percent of collisions happened during adverse surface conditions (19 percent when wet and 4 percent with ice, snow, or slush).

SAFETY IN WORK ZONES

The United States has a transportation system that is reaching its capacity limits. The infrastructure is aging and needs to be replaced. Therefore, to maintain mobility for drivers, roadway maintenance and construction must occur concurrently with traffic operations. Safety in work zones is essential, especially as the number of highway rehabilitation and construction projects continues to increase. Since 1983, the first year of data available, the National Work Zone Safety Information Clearinghouse reports a general rise in work zone fatalities as a percentage of the total number of highway fatalities (figure 2).[5]

Over the 10-year period from 1997 to 2006, work zone fatalities in crashes increased by 45 percent.[6] Although there was a marked drop in 2007 to levels not seen since the 1990s, work zone fatalities are increasing as a percentage of total fatalities. In the 1980s, work zone fatalities accounted for 1.5 percent of all highway fatalities, but this increased to 1.8 percent in the 1990s, and then to 2.4 percent since 2000, peaking at near 2.8 percent in 2002.[5] This equates to 717 fatalities in 1996 and 1,095 in 2003, or an increase of 35 percent.[7]

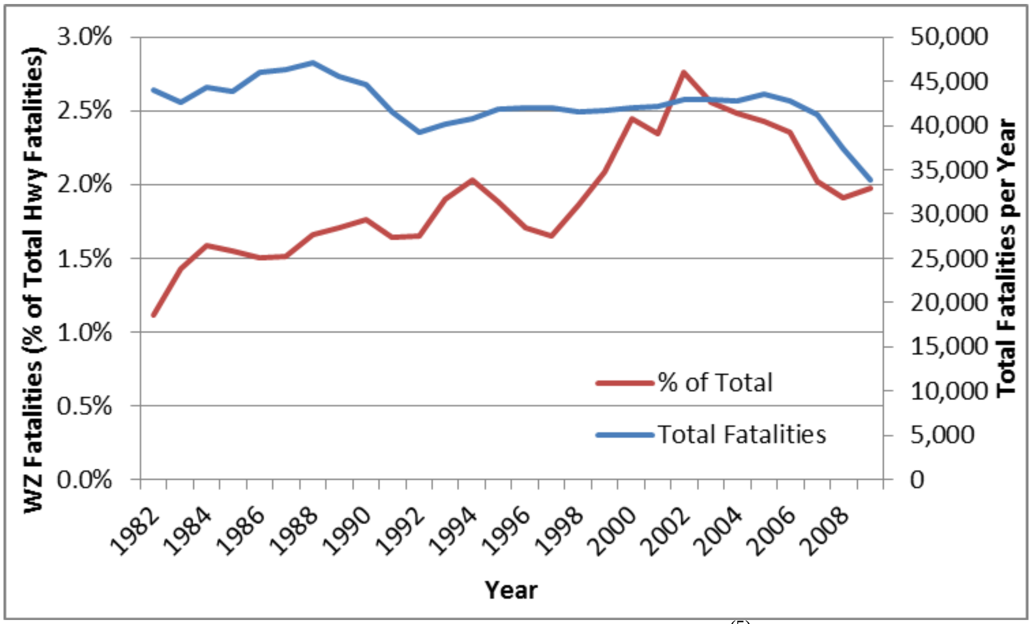


Figure 2. Graph. Safety in work zones.[5]

Work zone safety has become a larger issue over the years. Even as total annual fatalities have slowly dropped, the percentage of work zone fatalities (as a share of total fatalities) has increased. The increase in work zone fatalities is likely a result of increased amounts of maintenance activity on the nation's highways. Between 1997 and 2004, an increased share of construction costs was spent on existing facilities, growing from 47.6 to 51.8 percent of capital funds.[6] The FHWA also estimates that at any given time, 20 percent of some portion of each roadway in the National Highway System is under construction.[8] Additionally, the crash rate of any particular stretch of highway has been shown to increase by almost 30 percent during a construction period.[9] Although the percentages vary, another study also found that work zones greatly increase crash risks.[10] Lastly, according to the FHWA, approximately half of all fatal work zone crashes occurred at night.[6] This stresses the importance of visible pavement markings to help drivers navigate through work zones.

PAVEMENT MARKINGS

Standard Pavement Marking

The most common method of marking pavement is to spray pavement marking on the roadway surface and then drop glass beads with an index of refraction of 1.5 to make the markings more visible at night. The pavement marking, typically made of waterborne pavement marking, thermoplastics, epoxy, or solvent pavement marking, acts as a binder for the glass beads. Eighty-nine percent of State transportation agencies use waterborne pavement markings, which are the least expensive among these options.[11]

The retroreflective performance of the glass beads under given conditions depends on their refractive index (RI). Generally speaking, under dry conditions beads with an RI of 1.9 provide the highest retroreflectivity. Under wet conditions the RI needs to be greater, around 2.4, for high retroreflectivity because a film of water covering the beads changes the optical conditions that provide retroreflectivity.

An issue with conventional pavement marking systems is their poor performance in wet conditions. While dry, headlight illumination on pavement markings with 1.5 index beads typically provides sufficient guidance information to the driver. When covered by a layer of water, such as during rainfall, their retroreflective properties diminish. To a driver, it appears that the pavement markings have disappeared. The reason for this drop in performance is that the water reduces the amount of light that is retroreflected from the markings to the oncoming driver, due to a loss of effectiveness of the optical system. It becomes very difficult to see the pavement markings, and drivers have increased difficulty navigating a safe route.

To improve visibility of pavement markings in wet weather, 3M developed the AWP, which maintains retroreflective properties while covered with a film of water. The key to this technology is specially developed elements that provide retroreflection in both dry and wet conditions. After the AWP is sprayed on the road surface, 3M bonded core elements are dropped, followed by a second drop of conventional glass beads. Figure 3 shows a comparison of standard pavement marking and the AWP during a typical rain event in Henderson, North Carolina. The AWP, when applied correctly, is visibly more retroreflective.

Figure 3. Photos. Wet weather comparison of standard pavement marking (left) and the AWP (right) pavement markings.

The AWP Marking

Each 3M element is composed of a structural core surrounded by microcrystalline ceramic beads that have a range of higher refractive indices.(12) The refractive indices of the small attached beads are 1.9 and 2.4, compared to the typical 1.5 used in most standard pavement markings. The beads with a refractive index of 1.9 perform well in dry conditions, while the beads with the higher RI of 2.4 perform well in wet conditions, thereby improving overall visibility for the driver in a variety of weather conditions. Figure 4 displays a side-by-side comparison between standard pavement marking and the AWP marking.

The AWP binds the larger glass beads and the 3M elements to the pavement. According to 3M's website, "3M All Weather Paint includes a 'high-build' resin to enable thicker application for lines that last up to twice as long as conventional traffic pavement marking," and is manufactured with a high-build polymer emulsion.(13) The pavement marking is ideal in locations where other existing waterborne equipment is available.(12) It is applied at 25 mil (.635 mm) wet thickness, providing a very thick, wear-resistant layer of pavement marking.

Figure 4. Photos. Comparison between standard pavement marking (left) and the AWP marking with microcrystalline ceramic beads (right).

To optimize the construction, 3M tested various mixtures of beads and elements, drop rates, and pavement marking thicknesses. Due to the variations possible, there is an opportunity for customization and optimization. The mixtures for this test were selected from 24 candidate samples of pavement markings tested on a New Orleans, Louisiana, test track in November 2007.(14) These candidates were measured for their retroreflectivity under dry and wet conditions over a period of 6 weeks. The degradation of the different mixes varied—elements and glass beads became loosened from the binding pavement marking and scattered away due to repeated traffic passes—and only those that performed well were recommended for future tests.

Later, the Texas Transportation Institute, using the field research facility at the Texas A&M University Riverside Campus in Bryan, Texas, performed a human factors study to determine drivers' ability to see the AWP.(14) The driving course, outfitted with a rain range able to simulate rainy conditions, was sprayed with the pavement marking mixes that had performed well on the New Orleans test track. Two test segments were set up, once under the rain range and once elsewhere on the course for a dry weather comparison. Researchers first subjected drivers to the dry weather nighttime drive-through. Participants would announce when they were first able to see the end of the pavement marking, and the researcher would note the distance the vehicle was at that time. Next, the drivers were instructed to drive through the rain range where the wet conditions were simulated and similarly announced when they could view the end of each pavement marking. From these tests, one pavement marking mix was chosen to be implemented in the field due to its better visibility. The specifications provided are:

> 3M medium-sized high refractive index dual-optics drop-on elements at a drop rate of 8g/lineal ft in combination with MODOT Type P (or AASHTO M247 Type I).1.5 index glass beads at a drop rate of 12g/lineal ft applied in a double-drop onto a high-build waterborne pavement marking applied at a 20 mil [.508 mm] wet film thickness.

Safety Effect

Lane markings influence driver behavior continuously, and they are one of the most common ways drivers receive information about the roadway alignment ahead. Their presence helps influence the driver's position on the road, specifically within a travel lane. The position of a vehicle in a lane has a high correlation with safety, with correlation coefficients typically between 0.7 and 0.8, showing that the existence of pavement markings to guide the driver is extremely important. To ensure drivers have adequate guidance at night, the pavement marking's retroreflective properties must provide sufficient visual detection distance. Rumar and Marsh concluded that drivers need between 3 and 5 seconds of "preview time" to guide their vehicle.[15] They describe that, "in night driving, the single-vehicle crash risk increases proportionately with the decrease of average geometric sight distance" and that "this is an indication of the importance of longer preview times." Pavement markings that do not have high retroreflective properties put drivers at risk at night.

Pavement markings are also influential on a driver's speed, but the precise nature of that influence is unclear. Improved lane markings have reportedly increased speeds, but speeds have also dropped in some locations.[15] Speed increases are likely to happen because drivers have an increased amount of information being provided to them about the roadway ahead. This increases driver confidence to navigate the road, allowing an increase in speed. However, it is still to be determined if this increase in speed creates a safety risk.

Rumar and Marsh focused their study on visibility to evaluate pavement markings, as opposed to the crash rate, which they rejected as being inconclusive. They also hesitated to use speed, lateral placement, and the number of overtakings as measures of effectiveness.[15] Detection distance was identified as the most important aspect to the researchers. Emphasizing their case, the authors discussed several studies on the visibility of lane markings and retroreflectivity. Their paper presents examples of where lane markings give great benefit, such as at night, when a driver's point of fixation moves down and to the right, to avoid the bright lights of oncoming vehicles. Here, edge lines become critical for the driver to navigate the roadway safely.

Emphasizing visibility at critical times, Jacobs et al. discussed pavement markings in rainy conditions.[16] The study looked at several pavement marking products that differed in performance properties during wet conditions. Drivers were asked to drive a section of road where the pavement markings changed from traditional to all-weather performance. The drivers were to indicate when they noticed the change in the pavement marking products. The distance from where drivers indicated that they noticed the change to where the pavement marking actually changed was the primary measure of effectiveness and was obtained during dry and wet conditions. Table 1 displays the comparison table from that study; however, it should be noted that the samples taken in wet and dry conditions were not comparable and must be read independently. The authors strongly articulated that, in these situations, lane markings are most necessary, but they are prone to fail more often at these times. Such concern is what the AWP pavement markings are intended to address, especially in temporary application such as work zones.

Table 1. Nighttime visibility of painted and thermoplastic centerline and edge line markings under low-beam illumination.[16]

Condition of markings	New		Old	
Condition of road	Dry	Wet	Dry	Wet
No oncoming glare	164-285 ft (50-87 m)	112-125 ft (34-38 m)	98-213 ft (30-65 m)	89-108 ft (27-33 m)
Oncoming low-beam glare	164-253 ft (50-77 m)	131-164 ft (40-50 m)	98-131 ft (30-40 m)	98-131 ft (30-40 m)

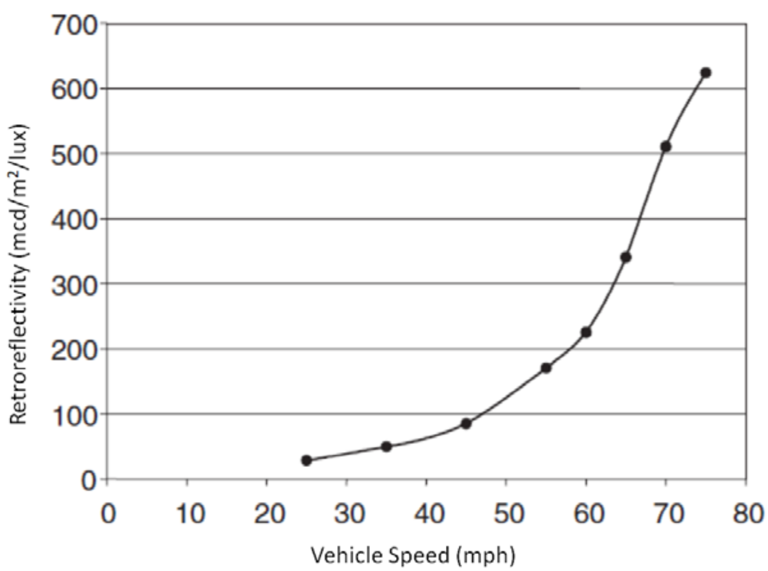
MEASURES OF EFFECTIVENESS

Carlson et al. chose two conflict MOEs to study the effect of pavement markings in rural high-speed maintenance work zones.[17] They considered 14 different conflict types and found only 2 applicable to work zones. The first was the slow vehicle conflict, which involves a faster vehicle overtaking a slower vehicle. The second was the lane change conflict, where a vehicle needs to brake to switch travel lanes because of a lack of gaps in the other lane, or a vehicle changing lanes and forcing vehicles behind it to brake or swerve when there was not a large enough gap.

In Phase I of this study, the researchers identified three additional MOEs.(18) The Phase I report stresses the importance of these MOEs and describes the following as necessary for evaluation of the new pavement markings: mean of the lateral placement of the vehicle in the travel lane, variance of the lateral placement of the vehicle in the travel lane, and number of times the vehicle touches the edge markings. The first two MOEs are correlated with crash frequency. There is a long tradition in the field that vouches that edge markings can be related to crash frequency as well. Increases in the inadvertent contact of the edge markings is a result of drivers varying their position in a lane away from the center, and a reduction would indicate increased safety benefit.

RETROREFLECTIVITY AND SAFETY

The retroreflectivity of pavement markings is defined by the coefficient of retroreflected luminance, usually expressed in units of millicandela per meter squared per lux (mcd/m^2/lux). Higher values indicate that the marking will appear brighter when illuminated by a set of headlights. Thus, a higher value of retroreflectivity should provide a longer detection distance and enable drivers to make earlier navigation decisions. As speed increases and drivers have less time to make judgments, it is critical that the pavement markings are still detected at distances that adequately inform users of the road geometry ahead. In Schieber's study on aging drivers, he showed how retroreflectivity needs increase at a higher rate than speed, as seen in figure 5.(19) Schieber also described how higher retroreflectivity is critical for aging drivers whose vision has decreased.



1 mph = 1.6 kph

Figure 5. Graph. Minimum pavement marking retroreflectivity requirements as a function of speed.(19)

Opposing arguments for high retroreflective pavement markings exist. Bahar et al. found that increased retroreflectivity in longitudinal pavement markings does not have any safety benefit.(11) Their claim is that the most important aspect of pavement markings is that they be present and visible for drivers; the level of brightness of the pavement markings is of less importance to safety. The argument is that drivers adapt to higher retroreflective markings and increase speeds due to increased confidence of the road ahead, thereby negating the safety benefit. Higher speeds place the driver at risk for more frequent and higher severity crashes.

Summarizing past literature, Bahar et al. described how the relationship between retroreflectivity and nighttime crashes has not been sufficiently proved. Likewise, Lee, Maleck, and Taylor were unable to identify any relationship between nighttime crashes and the retroreflectivity of pavement markings[20] Another study, by Abboud and Bowman, compared long-term crash rates to the average crash rate of crashes influenced by line visibility.[21] Although this study recommended a minimum value of retroreflectivity, Bahar et al. disputed the data analysis methods used. Bahar et al. studied the safety effect of pavement markings themselves and found that no pattern of improved safety exists as retroreflectivity is increased. Ultimately, they concluded that any safety effect is too small to detect, and the brightness of lane markers shows no increase in safety. They also reported that driver adaptation minimizes road safety improvements even in adverse weather conditions.

SITE SELECTION

SITE SELECTION CRITERIA

All aspects of this study took place in work zones. Work zones require drivers to make decisions that are not typical to normal driving operations, putting their cognitive processes under additional stress. For this project, crossovers were the chosen work zone maneuver for study, as opposed to lane drops or other maneuvers. Crossovers occur when traffic is diverted away from the existing roadway onto a temporary roadway section and then reintroduced to the existing roadway (this maneuver is typical when a bridge is being reconstructed and drivers are diverted onto a temporary bridge). Crossovers typically have less signage and information conveyed to the user, increasing the driver's need for pavement markings or other devices installed along the roadway for navigation. For example, at crossovers through the construction site, information is conveyed to the user through special means such as cones, barrels, and temporary signage. To remove the effect that other devices may have on drivers' ability to navigate a crossover, 3M provided certain site requirements and desired characteristics of candidate work zones. With only minor deviations, these requirements were communicated to members of the research team before the project began, and included:

General Site Requirements

- Work zone open for a minimum duration of 3 months.
- Four or more lanes on the highway (two lanes per direction of travel).
- No roadway lighting, if possible, especially construction lighting. If lighting is necessary, it should be approved and kept to a minimum.

Desired Site Characteristics

- Posted work zone speed limit of 45 miles per hour (72 kph) or higher.
- State, US, or interstate highways.
- Substantial lane shifts; for instance, no short crossovers to the shoulder (less than one lane width).
- No temporary RPMs. These typically are installed on all work zone applications in North Carolina and as necessary in Ohio.
- If jersey barriers are utilized at the site, no paddle reflectors installed on the top of the barriers.
- A good pavement marking contractor, as indicated by the State department of transportation (DOT).
- A history of multiple rainy days on record in the construction work zone season.
- No traffic signals in or near the crossover being studied.

In addition, in Phase I of the present study, the researchers concluded that a total sample of 250 vehicles was necessary to determine a 0.05 level of significance in differences in lane line encroachments.[18] At this value, it should be possible to detect differences between the experimental and standard pavement markings and their interactions with wet conditions.

Using these criteria, the research team worked closely with DOTs and nearby municipalities to find sites that would be suitable for study. Sites that were considered were all under construction during the 2009-2011 construction seasons. Additional criteria the team used to choose sites included:

- Two crossovers (entering and exiting the construction zone) so that one of the crossovers is utilized as a comparison site with standard pavement markings.
- Moderate to high traffic volumes that would meet the sample size requirements.
- Manageable implementation timeframes.

- Proximity to research team base to get to a site quickly during potential rain events. Sites within a radius of approximately 1 to 1.5 hours were preferred; however, in special circumstances, sites within a 4-hour drive were considered feasible.

Site types of interest included bridge replacements, resurfacing and rehabilitation of roadway surfaces, and widening. The effect of the economy on road construction and the requirements necessary (especially number of lanes and time to site) posed a major challenge to members of the research team. Table 2 shows a list of sites. The Lanes column shows the number of lanes that remained open through the crossover in one direction of the highway; all highways had four lanes originally.

Table 2. Field test site descriptions.

Roadway	Location	Type	Lanes	Speed Limit
I-85	Henderson, NC	Interstate	1	55 mph (89 kph)
US-15/501	Chapel Hill, NC	US Route	2	45 mph (72 kph)
US-421	Winston-Salem, NC	US Route	2	55 mph (89 kph)
US-32/33/50	Athens, OH	US/SR Routes	1	55 mph (89 kph)
I-90	Ashtabula, OH	Interstate	2	55 mph (89 kph)

SITE DESCRIPTIONS

I-85, Henderson, North Carolina

This project was a rehabilitation of several miles of I-85, designated North Carolina DOT Transportation Improvement Project (TIP) #I-2810. Henderson is located in the Northern Piedmont. During the data collection months of May and June 2009, the average monthly rainfall was above 3.6 inches (9.5 cm) and had a minimum of 9 hours and 22 minutes between sunset and sunrise.[22] During the period of construction, southbound I-85 was repaved, including some bridge rehabilitation. Median crossovers were utilized to bring traffic from southbound I-85 to the inside lane of northbound I-85. The north and south crossovers are approximately 6 miles (9.7 km) apart, shown in figure 6. Figure 7 shows daytime and nighttime views of the right curve into the treatment crossover on the south end of the work zone.

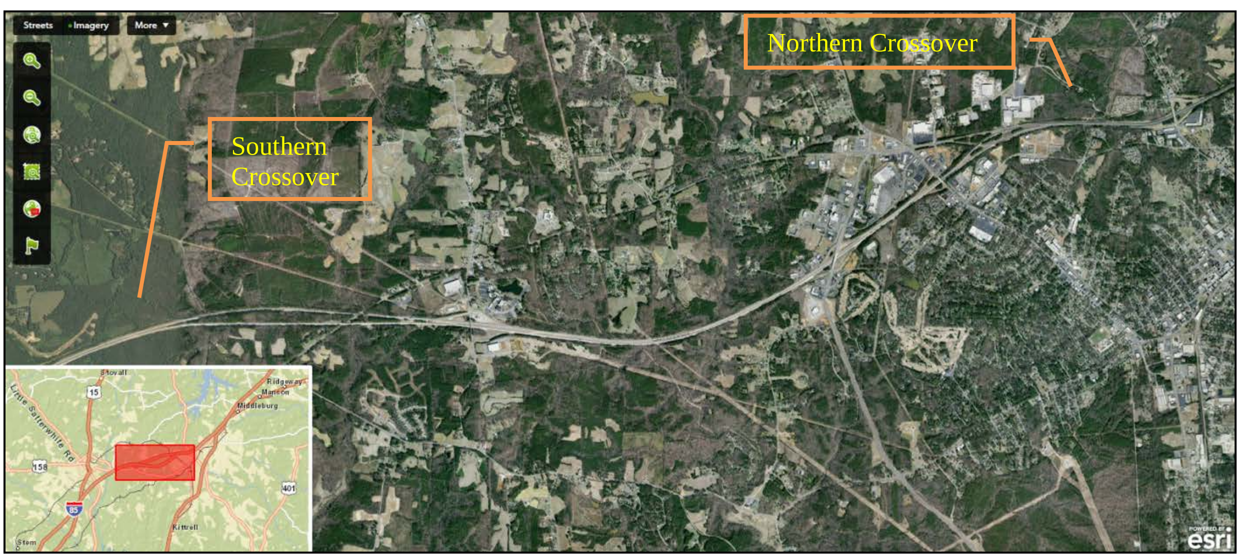


Figure 6. Photo. I-85 crossover locations.

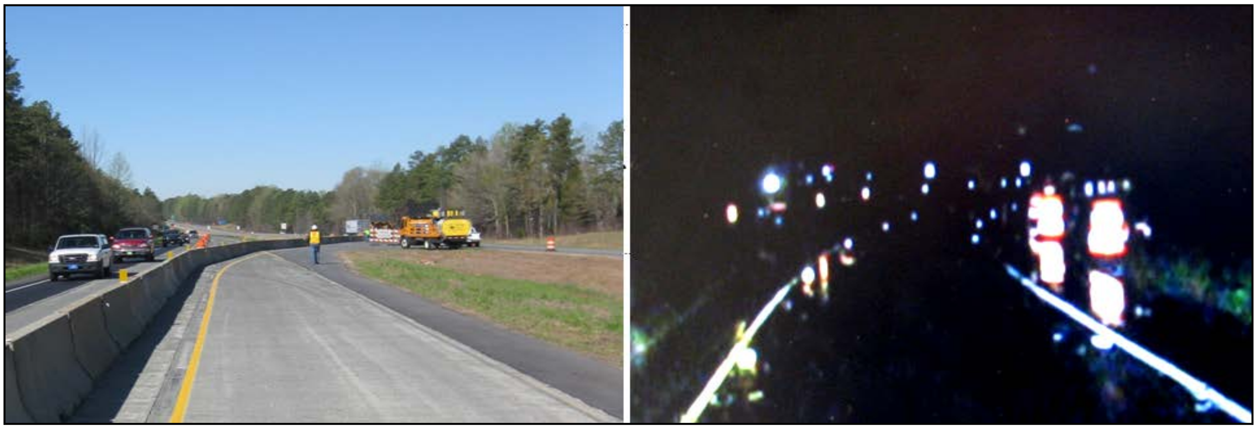


Figure 7. Photos. I-85 southern crossover during daytime and nighttime.

During the construction phase, traffic were reduced to one travel lane in each direction prior to entering the study area, using the original northbound travel lanes in a two-lane, two-way traffic pattern. At the time of the initial site selection process, the research team was not aware of the desire to study multiple lanes shifting into and out of the work zone. Because a sizeable effort was made to install data collection equipment, the site was kept for further data collection and analysis to note any differences between this site and other sites with multiple lane crossovers studied in this project. In addition, retroreflectivity studies were not affected by the need for more than one lane of traffic, so those findings are included in the summary findings. Figures 8 and 9 show aerial views of the southbound traffic shift at the northern and southern crossovers.

Figure 8. Photo. Aerial view of northern crossover. Southbound traffic shifts to northbound side divided by a jersey barrier.

Figure 9. Photo. Aerial view of southern crossover. Southbound traffic shifts back to normal operation.

Standard and the AWP markings were installed at the crossovers located along southbound I-85. The northern crossover was marked by the standard pavement marking specified in the construction plans and included RPMs and traffic barrels. The southern crossover was marked by the AWP, traffic barrels on the passenger side, concrete barriers with reflectors on the driver side, and RPMs. Based on recommendations in the literature, a minimum 5-second preview time was utilized with the AWP on the southern crossover, corresponding to a 500-foot (152.4 m) application of the AWP along the tangent just prior to first radius of the crossover.[17] The speed limit was 65 miles per hour (105 kph), but a $250 speeding penalty was in effect and was affixed to speed limit signs throughout the site. Speeds were under enforcement along a tangent section in the northbound direction during many of the initial site visits the research team made early during the construction process, especially during daytime operations. No data were collected while enforcement was taking place.

Both the comparison and treatment sites had S-curve geometry. After some discussion with North Carolina DOT inspectors and the pavement marking contractor, it was decided that the last curve exiting the work zone on the southern site (treatment) could not be tied into the regular lanes with the AWP because there was not enough time to switch out the elements and properly calibrate the pavement marking thickness and element drop rate, all while slowly rolling traffic through the work zone. This meant the final curve (left turn of the treatment site) could not be studied. Thus, the right turns for the northern and southern crossovers would be the focus of study for this particular site for comparison of speeds and lane encroachments.

Another issue that the project team noted at the northern end of the test site was the atypical manner in which I-85 was reduced to one lane (see figure 7). At a single point, drivers are forced to choose between veering left onto I-85 southbound or staying straight to exit onto US-158. Drivers appeared confused by this arrangement; many cars were observed making last-second lane changes less than 200 feet (61 m) from the delineating barrels. Other drivers were seen coming to a complete stop on the highway to decide which way to go. Furthermore, some drivers would make the wrong choice, quickly pull off onto the shoulder, and either reverse down the highway or drive through the barrels separating the exit and I-85. Because the layout of the entry into the crossover was problematic, data were not collected during periods of obvious confusion. In addition, the first turn (left turn) into the comparison site crossover was not studied so that any other possible “confusion effect” was eliminated.

Last, it should be noted that the length of this site (approximately 6 miles [9.7 km]) could pose problems in the analysis. Rain duration and intensity could be very different at one crossover than at the other. To help alleviate any potential concerns, the research team only analyzed data 10 minutes after the obvious beginning of a rain event at each site and stopped 10 minutes before rain ceased.

In light of the various issues with this site and assumptions that had to be made, research team members recommend that any speed and lane encroachment effects should be evaluated carefully. This site should only be considered as potentially supplementing any findings from the other test sites.

US-15/501, Chapel Hill, North Carolina

This particular project was a bridge rehabilitation project approximately 0.9 miles (1.4 km) in length located on US-15/501 just north of Chapel Hill. Figure 10 shows an aerial photo of the entire construction site. The site is located near the Durham and Orange County borders, with US-15/501 intersecting I-40 approximately 1 mile (1.6 km) beyond the southern crossover point.

Figure 10. Photo. US-15/501 crossover locations.

After the completion of the first of two bridges, southbound traffic was transitioned over to the northbound travel way to a temporary bridge built adjacent to the existing bridge. Two temporary lanes of traffic were constructed and separated from northbound traffic with a barrier. After crossing the temporary bridge, traffic was redirected back into the original southbound lanes. This second crossover was the focus of this study because of the nearby traffic signal at the northern crossover, especially the queues that spilled back into the crossover from the exit. Figure 11 is a photograph of the southern crossover. The research team installed a mast with an omnidirectional camera to observe this southern crossover point during both analysis periods (see figure 12) as both pavement markings were installed at this location in a staggered fashion. During the data collection months of May and July 2010, the average monthly rainfall was above 4.1 inches (10.4 cm), and there was a minimum of 13 hours and 38 minutes between sunset and sunrise.[22]

Figure 11. Photo. US-15/501 southern crossover – standard pavement marking and the AWP study site.

Figure 12. Photo. Nighttime camera views of US-15/501 northern crossover.

Both crossovers were two-lane movements. The comparison crossover consisted of standard pavement marking and a median barrier adjacent to the left lane. The treatment crossover was similar in that the AWP and median barrier were the only devices providing information to drivers regarding the configuration of the travel lanes. The speed limit was 55 miles per hour (89 kph). Both the comparison and the treatment sites had S-curve geometry similar to that of the Henderson site. However, the curves were slightly less abrupt than at the Henderson site, with larger radii and longer curve lengths.

US-421, Winston-Salem, North Carolina

The Winston-Salem site was similar to the Chapel Hill site in that it was also a bridge rehabilitation project. This site is located on US-421 approximately 2 miles (3.2 km) from I-40, Exit 188, between South Peace Haven Road and Lewisville Clemmons Road. An aerial photo of the site is shown in figure 13.

Figure 13. Photo. US-421 crossover locations.

Temporary bridges were installed in each direction while new bridges were built in the existing locations. After the completion of these temporary bridges, traffic lanes were shifted onto them, with approximately 500 feet (152.4 m) of space between the bridge and each crossover. The research team monitored the eastern and western crossover points for both directions, as opposed to only one crossover point, which was the case at the US-15/501 site.

The lanes traveling eastbound were marked with standard pavement markings, designating it the comparison side. Consequently, the two westbound lanes were marked with the AWP, thus being the treatment side. Both sides had a barrier between the left travel lanes and the construction area that transitioned from barrels to concrete barrier and back to barrels. Additionally, during the course of the research, RPMs were installed on the comparison side, unbeknownst to the research team. Soon after finding out about the installation of the RPMs, a member of the team went to the site and, with the help of the North Carolina DOT, uninstalled them. This was done to obtain a fair and accurate comparison assessment of the visibility of the standard pavement markings and that of the AWP pavement markings.

The site was monitored using standard closed circuit television (CCTV) cameras, which were attached to two separate masts that were erected in the median a few hundred feet past the eastern and western crossover points looking directly down the lane lines. Figure 14 displays screen shots from the videos of the four curves. The use of two masts allowed the researchers to collect data for all four crossover points simultaneously. Because rain duration and intensity were the same on each of the crossovers, the simultaneous data collection was optimal for the data analysis. During the data collection months (May through October 2011), the average monthly rainfall was 3.5 inches (8.9 cm), and there were a minimum of 12 hours and 58 minutes between sunset and sunrise.[22]

Figure 14. Photos. Four curves at the US-421 test site.

US-32/33/50, Athens, Ohio

The US-32/33/50 project involved the reconstruction of the existing highway over a distance of approximately 2 miles. The Athens study site was located on US-32/33/50 between the interchanges with State Route 682 (SR 682) and Township Highway 60 (Blackburn Rd.). When US-33 and US-32/50 split near the end of the work zone, the study area continued on US-32/50 until just before Township Highway 60. The study area is shown in figure 15**.**

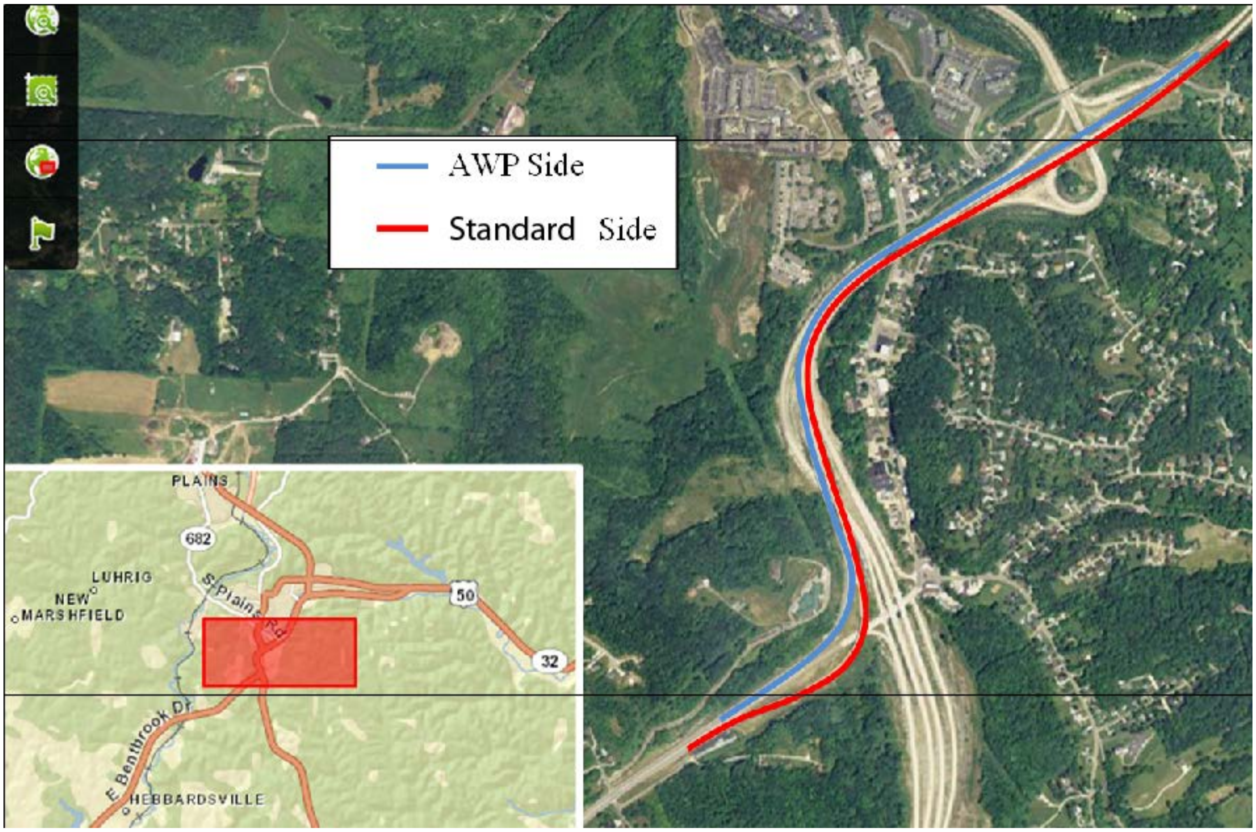


Figure 15. Photo. US-32/33/50 work zones.

According to the Ohio DOT, the annual average daily traffic (AADT) in 2009 for the section of US-32/33/50 was 17,960 vehicles per day, with trucks representing 8 percent of the total traffic. For the section of US-32/50, the AADT was 13,050 vehicles per day, with trucks representing 7 percent of the total traffic.(23) During the data collection months from April through June 2010, the average monthly rainfall was above 3.4 inches (8.6 cm), and there were a minimum of 12 hours and 39 minutes between sunset and sunrise.(22) The AWP was used for the work zone located along the eastbound lanes of US-32/33/50, while standard pavement marking was used for the work zone located along the westbound lanes. For each type of pavement marking, an area before, during, and after the lane shift was studied for the work zones. Figure 16 shows the work zones during the daytime hours, and figure 17 shows the work zones during the nighttime hours.

Figure 16. Photos. The AWP (left) and standard pavement marking (right) work zones on eastbound US-32/33/50 during the day.

Figure 17. Photos. The AWP (left) and standard pavement marking (right) work zones on eastbound US-32/33/50 at night.

While a site with a lane drop was not desirable, the site was selected due to proximity to the research office and capabilities of obtaining data during all weather conditions: daytime dry, nighttime dry, daytime wet, and nighttime wet. During construction, traffic was shifted over one lane to accommodate construction of half of the roadway at a time. The construction began during the spring of 2010 and continued through the fall of 2010. Data were only collected when the traffic was shifted to the inside shoulder of each direction of travel. During the construction, all exit ramps were open to traffic. Throughout each of the work zones the posted speed limit was 55 miles per hour (89 kph).

The data from this site were collected with video cameras mounted inside research vehicles that followed subject vehicles through the work zone. Data were collected for both directions of travel during the same time periods over several months. The amount of precipitation was noted during each rain event. As the data collection for the Athens site occurred over a several-week period, the average rainfall during the periods of data collection equaled 0.53 inches (1.3 cm) for the nighttime data collection and 0.54 inches (1.4 cm) for the daytime data collection.

I-90, Ashtabula, Ohio

The I-90 project involved the reconstruction of the existing concrete pavement over a distance of approximately 5.75 miles (9.3 km) between Paine Road in Lake County to the Ashtabula County Line.

Specifically, the Ashtabula study site was located on I-90 between the interchanges with State Route 11 (SR-11) and State Routes 84 and 193 (SR-84 and SR-193), as shown in figure 18.

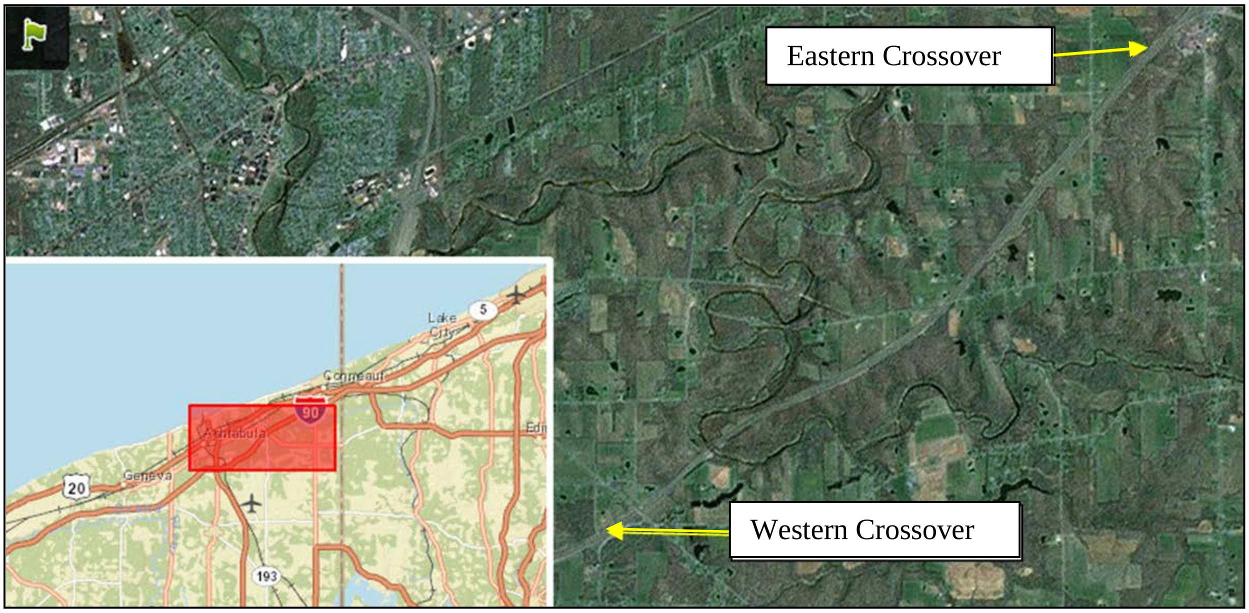


Figure 18. Photo. I-90 crossover locations.

According to the Ohio DOT, the AADT in 2009 for this section of I-90 was 22,910 vehicles per day, with trucks representing 30 percent of the traffic.[24] During the data collection months of August and September 2011, the average monthly rainfall was above 3.8 inches (9.7 cm), and there were a minimum of 11 hours 48 minutes between sunset and sunrise.[22] The AWP was used for the double-lane crossover on the eastbound lanes of I-90, as shown in figure 19**.** Standard pavement marking was used for the double-lane crossover on the westbound lanes of I-90, as shown in figure 20. Views of each of the crossovers from within a vehicle can be seen in figure 21.

Figure 19. Photo. AWP treatment location on I-90.

Figure 20. Photo. Standard pavement marking treatment location on I-90.

Figure 21. Photos. View of the AWP (left) and standard pavement marking (right) double-lane crossover.

During the construction period, the two eastbound travel lanes were shifted to the two westbound travel lanes through a two-lane crossover. After crossing the construction site, the eastbound travel lanes were shifted back to their original travel path. The construction of the eastbound travel lanes began in late November of 2010. At the onset of the project, neither the AWP nor standard pavement marking were installed along the two-lane crossovers due to concerns with temperatures at the site, which were substantially below the desired 50-degree Fahrenheit (10 degrees Celsius) temperature for installation of the pavement markings. In the interim, a fast-dry temporary pavement marking was utilized for the pavement marking with raised pavement markers throughout the work zone until the temperatures in the spring (April) were adequate to install the AWP and standard pavement markings.

Both crossovers utilized similar geometric features, such as a reverse curve with a radius of 3,125 feet (952.5 m). The total length of the western crossover was 1,095 feet (333.8 m), and the total length of the eastern crossover was 1,085 feet (331 m). Throughout the work zone, the posted speed limit was 55 miles per hour (89 kph) for both directions of travel.

Data at the Ashtabula site were collected with sensors along the entire length of each crossover. Due to the number of sensors required for each crossover, the data were not collected simultaneously on both crossovers. Therefore, the amount of precipitation was noted for each period to assure similar precipitation events were compared in the analysis. The cumulative precipitation occurring during the 2-hour data collection for the AWP was 0.34 inches (.86 cm), while the precipitation for the standard pavement marking was 0.42 inches (1.1 cm). As the rainfall amounts were similar during the nighttime data collection periods, rainfall was not considered a confounding variable.

DISCUSSION OF POTENTIAL FOR DATA COLLECTION

The data collection for this project ultimately depended on the potential for rain events during nighttime conditions. The research team looked into the potential for data collection at each of the five sites by summarizing the average rainfall and nighttime hours during each month of the year, as shown in tables 3 and 4. Average rainfall totals are provided as the average monthly rainfall from 2003 to 2008. The available time for data collection during nighttime hours was calculated as the available time between ensuing darkness (30 minutes after sunset) and midnight, after which it was assumed that data collection probably was not feasible due to low traffic volumes and extended team travel time.

Table 3. Average monthly rainfall totals (inches).[22]

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Henderson, NC	3.6	3.5	3.8	3.0	3.9	3.8	4.3	4.7	3.7	3.4	3.3	3.3
Chapel Hill, NC	3.7	3.9	4.3	3.3	4.5	4.4	4.1	4.4	3.3	3.5	3.5	3.5
Winston-Salem, NC	3.3	3.3	3.7	2.8	4.0	3.8	4.5	3.9	3.5	3.5	3.0	3.4
Ashtabula, OH	2.7	2.2	2.8	3.6	4.0	4.5	4.7	3.8	4.3	4.0	3.7	3.5
Athens, OH	2.6	2.7	3.3	3.4	4.4	3.7	4.4	3.3	2.8	2.7	3.3	3.0

1 inch = 25.4 mm

Table 4. Average available time for nighttime data collection (hh:mm).[22]

Location	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
Henderson, NC	6:08	5:35	5:09	4:42	4:17	3:57	3:59	4:26	5:09	5:52	6:25	6:30
Chapel Hill, NC	6:04	5:32	5:06	4:40	4:15	3:56	3:57	4:24	5:07	5:49	6:21	6:26
Winston-Salem, NC	6:00	5:28	5:02	4:35	4:10	3:50	3:52	4:19	5:02	5:45	6:17	6:22
Ashtabula, OH	6:10	5:55	4:49	3:45	2:54	2:53	2:57	3:29	3:58	4:30	5:55	6:52
Athens, OH	5:58	5:46	4:44	3:44	2:55	2:36	2:39	3:09	3:33	5:00	5:23	6:20

The rainfall totals were interesting. Surprisingly, the average rainfall for each of the sites is fairly constant over time, with little variation between the seasons of the year. However, the available data collection time improves during winter months, as the winter solstice takes place in mid-December. The earlier sunset also affords the potential for higher traffic volumes during data collection, since the researchers would be collecting a portion of the peak hour traffic in some cases. Therefore, sites studied during winter months have the higher likelihood of collecting larger samples of data because the nighttime data collection time period is longer and includes potentially higher total traffic volumes by including a portion of the peak period travel.

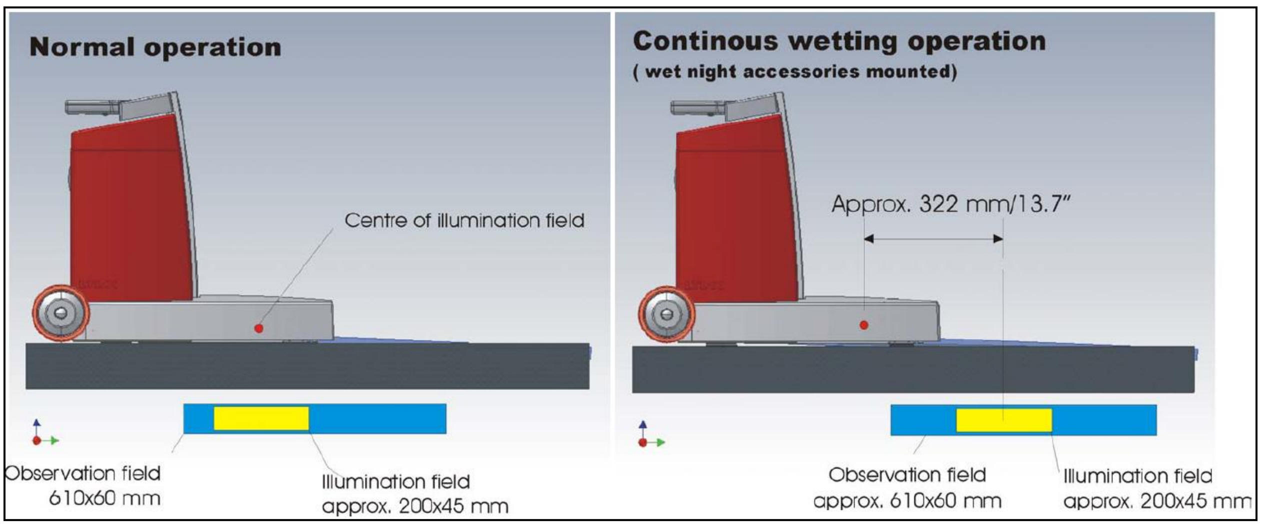
RETROREFLECTIVITY

Retroreflectivity is a measure of the ability of a sign, pavement marking, or other countermeasure to reflect light back toward the source (i.e., the driver in the car). The research team took retroreflectivity measurements of standard pavement marking and AWP during the same day the markings were applied. The team formally documented the field installations of each pavement marking type from four different contractors in two different States, each given basic training and/or guidance from 3M on the installation of the new AWP prior to installation. No guidance was given on how to install the standard pavement marking, allowing the research team to document real-world field installations currently used in practice based on the specifications given by the respective DOTs.

DATA COLLECTION

Retroreflectometer

The retroreflectometer used in this study is in accordance with the standard test method for measurement of retroreflective pavement marking materials: it has an illumination angle of 1.24 degrees and an observation angle of 2.29 degrees, simulating an observation distance of 98.4 feet (30 m). The illumination and observation fields are shown in figure 22. Note how the illumination field, when measuring retroreflectivity of a wet continuous pavement, is not immediately below the device, as opposed to normal operation. This shift occurs when the wet night rails are attached, allowing the machine to measure pavement continually wetted by a water sprayer directly in front of it. All tests were to be performed with the wet night rails attached, per 3M instruction.



1 mm = .04 inch

Figure 22. Diagram. Retroreflectance measurement fields.

Retroreflectivity values were collected approximately 30 minutes after the pavement markings were laid on the road surface. Before collecting retroreflectivity data, the section of pavement marking was swept to remove any loose optical elements and glass beads that did not bind to the pavement marking. This allowed for a more accurate retroreflective measurement because, over time, these elements would dislodge and scatter. One by one, three retroreflectivity tests were conducted on the test segment: the standard dry test (ASTM E1710-05), the wet continuous test (ASTM E2177-01), and the wet recovery test (ASTM E2176-01).

For the wetting of the pavement during the wet continuous test, the research team used a 4-gallon (15-liter) rechargeable sprayer. As suggested by 3M, the research team added a few drops of regular dishwashing soap to the water in the sprayer's reservoir, about 1 tablespoon (14.8 ml) for 3 gallons (11.4 liters) of water, which is enough to give the solution a very light tint. Per the ASTM test specifications, the water was sprayed on the pavement marking at a rate of 9 inches per hour, and retroreflectivity readings were measured until the displayed values were constant with each recording. The water spraying then ceased, and the wet recovery retroreflectivity value was measured 45 seconds after.

Retroreflectivity Test and Samples

Following the aforementioned procedures, retroreflectivity tests were conducted at four of the five test sites: I-85 (Henderson, NC), US-15/501 (Chapel Hill, NC), US-421 (Winston-Salem, NC), and I-90 (Ashtabula, OH). Retroreflectivity measurements were taken at the US-32/33/50 site (Athens, OH); however, immediately after the markings were applied for both sections (the AWP and standard pavement marking), the contractor sprayed water and applied straw to the median, which affected the measurements. Therefore, these data were not included in the analyses.

Sample sizes were dependent on the team's ability to collect data in various events. For instance, the Henderson site was a large facility that had a rolling road block. The first two rolling road blocks allowed each of the markings to dry. Then several more rolling road blocks were conducted based on the willingness of the contractor at the site. In all, a minimum of 10 retroreflectivity readings were conducted for each pavement marking type under the 3 simulated weather conditions (dry, wet continuous, and wet recovery). In addition, both yellow and white pavement markings were sampled. Table 5 shows the individual sample for each simulated weather condition for each pavement marking color and type. For example, in Henderson, 11 white treatment pavement marking readings was taken under dry conditions, followed by 11 separate wet and wet recovery readings.

Table 5. Retroreflectivity sample size obtained at each of the four sites studied.

Site		**Treatment (AWP)**		**Comparison (Standard)**	
		White	**Yellow**	**White**	**Yellow**
I-85	Henderson, NC	11	11	11	11
US-15/501	Chapel Hill, NC	10	10	10	10
US-421	Winston-Salem, NC	22	26	20	16
I-90	Ashtabula, OH	9	6	11	6

Neither the I-85 nor the US-15/501 data sets needed any reduction in the measurements taken. As for the US-421 test site, three retroreflectometer readings were taken on the temporary bridge installments on both directions of the highway for both white and yellow striping under each simulated weather condition. The bridge deck striping required additional thermo-treatment prior to pavement marking installation. The inclusion of thermoplastic greatly enhanced the retroreflectivity and would bias the results; therefore, these measurements taken on the bridge decks were removed from the samples to be analyzed.

ANALYSIS METHODOLOGY

At each test site, there were a variety of different retroreflectivity measurements. The three factors that distinguished results included (1) pavement marking treatment (the AWP or standard pavement marking), (2) pavement marking color (white or yellow), and (3) simulated weather conditions (dry, wet continuous, or wet recovery). Therefore, each site had 12 distinct retroreflectivity measurement sets. The measurement sets, defined by the combinations of factors, are listed in table 6.

Table 6. List of retroreflectivity samples at each site.

Retroreflectivity Samples			
#	**Pavement Marking Treatment**	**Pavement Marking Color**	**Simulated Weather Condition**
1	AWP	White	Dry
2	AWP	White	Wet Continuous
3	AWP	White	Wet Recovery
4	AWP	Yellow	Dry
5	AWP	Yellow	Wet Continuous
6	AWP	Yellow	Wet Recovery
7	Standard	White	Dry
8	Standard	White	Wet Continuous
9	Standard	White	Wet Recovery
10	Standard	Yellow	Dry
11	Standard	Yellow	Wet Continuous
12	Standard	Yellow	Wet Recovery

For each sample, the average and standard deviation were calculated. A standard two-sample t-test was conducted assuming unequal variances. Samples treated with the AWP pavement marking were compared to standard pavement marking treatment samples of the same striping color under the same simulated weather condition, and at the same locations for each weather condition. Finally, for each comparison, the percent difference between retroreflectivity averages was calculated.

RESULTS

There were marked differences observed between retroreflectivity readings at each of the three sites even when treatments, striping colors, pavement type, and weather conditions were the same. Therefore, sites were rendered independent of one another, and the samples were analyzed separately.

For each site, the averages and standard deviations were calculated for the two types of pavement marking systems installed for both white and yellow striping under the three simulated weather conditions. The mean difference was calculated by subtracting each standard pavement marking average (baseline) from the AWP average. The percent difference was found by dividing the mean difference by the baseline standard pavement marking average. An unpaired two sample t-test was used to compare all the AWP samples with standard samples. The significance level was set to a 95 percent confidence interval. The null hypothesis assumed that the two pavement marking samples had similar retroreflectivity measurements. All four sites are summarized in table 7.

Table 7. Summary of statistics for retroreflectivity readings at all test sites.

Site	Marking		White Dry	White Wet Continuous	White Wet Recovery	Yellow Dry	Yellow Wet Continuous	Yellow Wet Recovery
I-85 (Henderson, NC)	Standard	Avg.	344.6	220.0	315.7	155.5	101.4	137.7
		Std. Dev.	24.6	12.8	21.9	17.3	15.3	17.7
	AWP	Avg.	740.7	464.0	679.8	561.4	386.0	461.5
		Std. Dev.	65.4	202.2	87.8	70.2	77.5	35.6
	Mean Difference		+396.1	+244.0	+364.1	+405.9	+284.6	+323.8
	Percent Difference		+114.9%	+110.9%	+115.3%	+261.0%	+280.7%	+235.1%
	P(T<=t) two-tail		< 0.001*	0.0042*	< 0.001*	< 0.001*	< 0.001*	< 0.001*
US-15/501 (Chapel Hill, NC)	Standard	Avg.	166.2	10.2	9.3	122.6	8.8	37.9
		Std. Dev.	40.7	1.7	9.8	20.9	1.0	9.2
	AWP	Avg.	507.2	107.6	294.5	418.5	44.6	223.0
		Std. Dev.	175.4	39.2	123.9	133.0	16.8	76.3
	Mean Difference		+341.0	+97.4	+285.2	+295.9	+35.8	+185.1
	Percent Difference		+205.2%	+954.9%	+3066.7%	+241.4%	+406.8%	+488.4%
	P(T<=t) two-tail		< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*	< 0.001*
US-421 (Winston-Salem, NC)	Standard	Avg.	274.9	37.9	54.7	194.0	22.5	26.7
		Std. Dev.	33.1	10.0	13.4	12.9	8.0	3.6
	AWP	Avg.	463.2	39.8	140.4	372.6	36.8	165.7
		Std. Dev.	36.0	17.9	41.4	41.1	12.2	26.5
	Mean Difference		+188.3	+1.9	+85.7	+178.6	+14.3	+139.0
	Percent Difference		+68.5%	+5.0%	+156.7%	+92.1%	+63.6%	+520.6%
	P(T<=t) two-tail		< 0.001*	0.69	< 0.001*	< 0.001*	< 0.001*	< 0.001*
I-90 (Ashtabula, OH)	Standard	Avg.	110.5	5.3	9.0	35.5	4.0	2.7
		Std. Dev.	32.3	1.7	3.5	9.7	0.8	1.9
	AWP	Avg.	536.1	17.2	230.3	263.2	17.4	166.2
		Std. Dev.	167	6.3	88.7	44.4	5.7	68.9
	Mean Difference		+425.6	+11.9	+221.3	+227.7	+13.4	+163.5
	Percent Difference		+79.4%	+69.2%	+96.1%	+86.5%	+77.0%	+98.4%
	P(T<=t) two-tail		< 0.001*	< 0.001*	< 0.001*	< 0.001*	0.002*	0.002*

Retroreflectivity in $mcd/m^2/lx$.

* p-value is statistically significant (α = 0.05)

The p-values for the overwhelming majority of retroreflectivity tests were less than the significance level selected (α = 0.05); therefore, the null hypotheses that the two pavement markings had similar retroreflectivity measurements were rejected. The results of the t-tests imply that a statistically significant difference can be expected between the AWP and standard pavement markings' retroreflectivity during all three weather scenarios and pavement marking colors at each individual site. Major improvements were noted across the board when the AWP was used; however, the most significant findings were in the increased retroreflectivity results for yellow pavement marking. In general, yellow pavement marking was less reflective than white pavement marking for standard marking and the AWP, so the notable increase in retroreflectivity could be very important for transportation agencies.

Research team members cannot readily explain the major differences in retroreflectivity between sites. Two possible theories may explain the differences. First, although a 3M representative was on-hand for the calibration of machinery and during the actual application of the pavement markings, the research team suspects there was some human error during the application process due to the differences in machinery used and experience and comfort of the team in actually applying different pavement marking mixtures. If this is true, pavement marking applications should be expected to have a lot of variability, which suggests that minimum pavement marking retroreflectivity standards should be considered by public entities (indeed, many agencies use such standards). Second, the team suspects that there may have been differences in results based on the ability of the pavement marking to shed water in some instances, possibly due to differences in pavement type, pavement roughness, or maybe even grade or crown in various roadways studied. Unfortunately, this possibility was not accounted for in the analysis.

CONCLUSIONS AND RECOMMENDATIONS

As shown in table 7, based on the collection of retroreflectivity readings and the statistical analysis, it may be concluded that, when correctly installed, the AWP markings will provide a statistically significant increase in retroreflection when compared to standard pavement markings. In addition, the variability in the retroreflectivity readings for both pavement markings types being studied suggests that pavement marking contractors are not using consistent methods for applying their pavement markings.

In this study, the retroreflectivity readings were taken only after the initial installment of pavement markings. As the temporary work zone markings are expected to last at least 1 year, it is suggested that further investigation be conducted in examining how the AWP markings degrade over varying periods of time and under various traffic conditions.

Validating that the AWP markings were indeed more retroreflective, the research team further sought to examine whether these pavement markings would increase lane visibility and thereby improve navigation through work zone detours under nighttime, rainy conditions. The measures of effectiveness, including speeds, lane encroachments, and lane deviations, are discussed in the following chapters.

SPEEDS

AWP has been proven to be more retroreflective than the standard pavement marking. As a follow-up to that finding, the research team sought to discover how this new pavement marking affects driver behavior. The analysis of speed data was used as an indication of a motorist's perceived risk while traveling through a work zone guided by the AWP or standard pavement marking through lane shifts and crossovers. Comparisons are made between entry and exit curves for both standard and AWP.

DATA COLLECTION METHODS

LIDAR Speed Gun

Whenever possible, speeds were collected using a Class I laser speed gun. The speed gun uses light detection and ranging (LIDAR) technology, which uses a pulse of light that calculated the distance to the nearest vehicle 200 times per second, allowing for extremely accurate readings when calibrated. According to Laser Atlanta, the gun is capable of providing speeds within ± 1 mile per hour (± 1.16 kph). The speed gun is capable of acquiring its intended target in as little as 0.3 seconds, provided the user can acquire the target quickly and follow it with a steady hand. Speeds were recorded as vehicles were approaching or departing the location of the speed gun user, with no more than ± 5 degrees of angle between the user and vehicle being recorded to reduce any potential accuracy issues.

Two independent observers collected speed data concurrently in the crossover sections at the treatment and comparison locations when at the entry or exit in the same direction of travel. This meant that the population of drivers in the comparison and treatment speed bins was very similar as they entered and exited the work zone. In addition, the rain intensity at both segments was approximately the same throughout the entire data collection period. Of course, longer work zone segments likely had different rain intensities throughout the speed data collection time period; however, the differences were assumed to be negligible since data at longer sites were collected after a suitable period of time elapsed once rain was observed at both sites. If a platoon of vehicles was observed, the lead vehicle of the platoon was recorded as a single measurement and the following vehicles were ignored. This allowed the team to only collect speed data on vehicles that were maneuvering through the crossover at a safe speed as determined by the driver of that particular vehicle. Following vehicles would have likely been affected by the lead vehicle's decision about what the safe traversing speed was for the curve and would not have been a true representation of what that driver's speed may have been if not following a platoon.

Video Calculated Speeds

Speed data also were calculated from videos taken at the I-85, US-15/501, US-421, and US-32/33/50 test sites. The research team had three motivations for using videos to collect speed data. First, this method allowed speeds to be obtained during rain events at site locations farther from the research team's offices (i.e., those requiring longer travel times), especially when the probability of a rain event was low. Second, speed samples could be collected for the exact same drivers through both crossovers at the same location every time, whereas the speed gun measurements included some human error in obtaining speeds at the same location in the transition every time. Third, video was required for lane encroachment analysis and was readily available for speed usage. Using the video taken to collect lane encroachments and volumes, speeds were collected from the same populations examined for lane encroachments rates.

The primary drawbacks to this method were two-fold. First, there is human error when using a stopwatch and known distance to collect speeds. To counter this, a time-stamp overlay was utilized to obtain accurate times within 1/30th of a frame. Second, the angle to the crossover where speeds were taken meant that some occlusion existed. Since occlusion was consistent at all known points, we assumed this to be consistent among all measurements.

Speeds were calculated in the following steps:

1. Record for no less than 2 hours at each curve.
2. Take physical distance measurements at each curve.
3. Calibrate measurements with the speed gun.
4. Watch the videos in the lab and record the times it took lead vehicles to traverse the measured distances.
5. Calculate speeds using timing macros and functions in a computer-based database program.

Sensor Calculated Speeds

The research team used sensors to determine the speeds of vehicles traveling along the two-lane crossover on I-90. The sensors were located at 100-foot (30.5-m) intervals along the right and left travel lanes for the eastbound direction in which the AWP pavement markings were utilized. Along the westbound direction of travel, in which the standard pavement marking were utilized, the sensors were only located along the right travel lane due to the lack of an inside shoulder. The speeds were calculated by dividing the spacing of two sequential sensors by the time taken by a vehicle to traverse the distance between the sensors.

The sensors included a SHARP distance measuring sensor unit (Part No. GP2Y0A710K0F) and a MicroStrain SG-Link® Wireless Strain Node. The SHARP sensor was composed of a position-sensitive detector, infrared emitting diode, and a signal processing circuit, which provide a voltage output that corresponds to the detection distance (SHARP, 2006). The operating range for the SHARP sensors is 3.28 to 18.05 feet (1 to 5.5 m). The SG-Link® Wireless Strain Node was used to process the voltage output of the SHARP sensor and transmit it to a MicroStrain WSDA®-Base-mXRS™ Wireless Base Station connected to a laptop. The laptop connected with the Base Station had the MicroStrain Node Commander® software installed to conduct synchronous sampling for multiple SG-Link® Nodes. The SHARP sensor and the SG-Link® Node were installed in a plastic enclosure and were each connected to batteries for a power supply. The internal view of a sensor with the lid of the plastic enclosure removed is shown in figure 23. To securely place the sensors in the field, mounting bases were constructed using lumber, Velcro, and brackets. These mounting bases helped to elevate the sensors so they could measure the axle of the passing vehicle (opposed to the body of the vehicle) without being impeded by the cross-slope of the roadway. Also, the bases provided a means of securing the sensors to the graded shoulder. The sensor placed in the mounting base can be seen in figure 24.

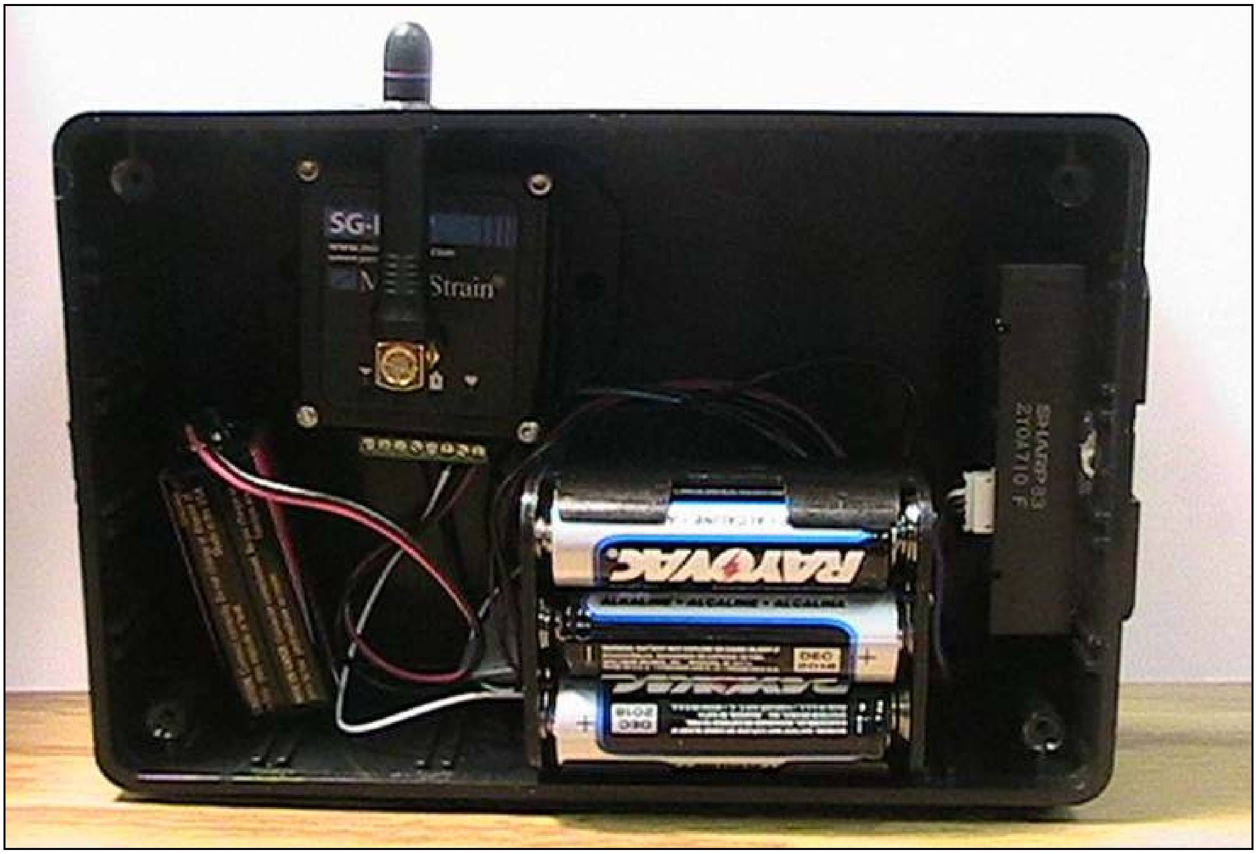


Figure 23. Photo. Internal view of sensor.

Figure 24. Photo. Sensor on mounting base.

Once the data were collected, the researchers needed to filter the data since there were continuous voltage readings for the entire data collection period. The team observed spikes in the voltage readings from a constant baseline level. This behavior is expected, as the output voltage increases as the detection distance decreases. Therefore, the baseline low voltage represents nothing present within the operating range, 3.28 to 18.05 feet (1 to 5.5 m). When the voltage increased above 1 volt, the sensor detected an object within the operating range. The researchers determined that to calculate speeds using the data collected, determining the initial voltage peak for each vehicle was necessary. This initial voltage peak would correspond to the front axle of the vehicle. As a result, a macro was created to filter through the data to find the initial voltage peaks. Once all of the readings were properly filtered, the sensor data, which produced a time-stamp for each collected reading, was utilized to determine vehicle speed. Theoretically, as a vehicle progressed through the crossover it would pass in front of each of the sensors and produce readings on each. Thus, the elapsed time from sensor to sensor can be determined by lining up the readings and, subsequently, the speed of the vehicle was calculated.

ANALYSIS METHODOLOGY

This section outlines the differences in data collection at each of the sites, any particular problems with data collection, and sample sizes utilized during the data collection effort. Basic statistical analysis was conducted for the speed data collected at each test site after outliers were removed. First, averages and standard deviations were calculated from the filtered speed data. The samples' averages and mean differences were then compared and calculated. Two different statistical tests were utilized. For North Carolina sites, the unpaired t-tests assuming unequal variances were used to test the significance levels in comparing speed samples. For Ohio sites, analysis of variance (ANOVA) was used. All sites were independent of one another and required separate analyses.

I-85

The team sought to obtain speeds during nighttime rain events through the northern and southern crossovers at I-85 using a LIDAR speed gun. However, due to the variable nature of rain events and the lack of operators and equipment, the team was only able to record a single speed sample at each crossover. The two speed samples were taken from vehicles well within their respective crossovers. Samples of only 15 reliable speeds were taken in the northern crossover (standard pavement marking), and 46 were taken in the southern crossover (the AWP), each sample in a platoon only including the lead vehicle. The samples were a bit small for any confidence in statistical analysis, but they are nonetheless available.

Upon further investigation in the office, camera angles at the northern crossover allowed speeds to be obtained at the entry and exit curves. (Collecting speeds at the southern crossover using video was not feasible because the relative camera angles presented too much occlusion from vehicles to consistently and accurately confirm distance.) Although not the primary goal, the team found it useful to examine the possibility of mean speed differences at the entry and exit of this single crossover. From the video, sample sizes of 208 and 211 were collected from the northern crossovers' entry and exit curves, respectively. Outliers less or greater than 2 standard deviations were removed from the samples, reducing the sample sizes to 200 and 202, respectively.

Given the two speed samples, initially two separate statistical comparisons were conducted for data collected using both available samples. First, the mean difference was calculated for the northern and southern crossovers. As the sample sizes were small when comparing the AWP to standard pavement marking, the analysts decided against further analysis of this initial data set, since the findings could be incorrectly used with findings from other sites with similar analyses but much more data. Therefore, the only remaining speed analysis conducted at this particular site was from the northern crossover entry and exit curves. The two samples were compared using the unpaired two-sample t-test assuming unequal variances.

US-15/501

To obtain speeds at the US-15/501 test site, the team used the alternative video extraction method. As mentioned earlier, for this site only one curve was feasible for analysis due to the signal at the northern crossover. The research team worked with the pavement marking contractor and 3M to arrange for the AWP to be installed on top of the standard pavement marking after a series of rain event data had been collected on the standard pavement marking. After the AWP installation, video footage of nighttime rain conditions was again recorded from the same camera installation locations for future data extraction.

Although other samples of rainy nighttime data were available, only two samples were utilized: one sample during the time the lane shift was treated with standard pavement marking and the other after the AWP overlay. The primary reason for this decision was the team hypothesized that rain intensity would have a marked effect on drivers' ability to safely traverse the work zone, so comparisons of greatly different rain events were not examined.

During the data collection for standard pavement marking, the rain intensity was approximately 0.50 inches (1.27 cm) per hour, while the approximate rain intensity for the AWP overlay was 0.40 inches (1.0 cm) per hour. A sample of 218 speeds was collected when the site was treated with standard pavement marking, and 275 speeds were collected with the AWP. The sample size was sufficiently large; therefore, the analyst removed outliers beyond 2 standard deviations from both samples, thereby reducing the samples sizes to 212 speeds and 262 speeds for standard pavement marking and the AWP, respectively. The two samples were compared using the unpaired two-sample t-test assuming unequal variances.

US-421

As described earlier, the field setup for the US-421 site was ideal for data collection because of the two bridges being reconstructed simultaneously. Therefore, both entry and exit crossovers along each direction of travel were analyzed independently, which is detailed previously in figure 14. This allowed the research team to utilize four synchronized videos of each crossover location. Speeds were taken for over 200 lead vehicles at each of the curves.

In all, 240 and 248 speeds were recorded at the AWP entry and exit curves, respectively, and 219 and 233 speeds were recorded for the standard pavement marking entry and exit curves, respectively. Again, any speeds less than or greater than 2 standard deviations of their curve speed averages were deemed outliers and filtered from the data. After the data filtration, there were 227, 239, 205, and 220 speeds for the AWP and standard pavement marking curves. The t-tests conducted compared the AWP entry speeds versus standard pavement marking entry speeds, the AWP exit speeds versus standard pavement marking exits speed, the AWP entry versus the AWP exit, and standard pavement marking entry versus standard pavement marking exit during nighttime rain conditions.

US-32/33/50

To obtain speeds at the US-32/33/50 test site, the video extraction method was utilized. Based on the placement of the video cameras, the speed data could be extracted by subdividing the work zone into three separate sections: at the beginning of the lane shift, in the midpoint of the lane shift, and at the end of the lane shift. Due to the location of an exit ramp near the lane shift, any vehicle exiting the highway via the ramp was excluded from the positional speed analysis. Similar vehicles were utilized for the speed data extraction as well as the lateral lane placement data. Data were collected during daytime and nighttime rain conditions as well as during nighttime dry conditions through the months of May, June, and July 2010. The sample sizes for the data collection ranged from 54 vehicles to 121 vehicles due to the elimination of vehicles that were not lead vehicles in a platoon and those that did not continue through the entire lane shift.

The samples at the US-32/33/50 test site included speeds along the travel lanes for entering, within, and exiting the lane shifts for both the AWP pavement markings and the standard pavement markings. A one-way analysis of variance was conducted to compare the speeds using several hypotheses, listed below:

- Mean speeds were similar for entering, within, and exiting lane shifts for the AWP and standard pavement marking sites.
- Mean entering speeds were similar for the AWP as compared to the standard pavement marking.
- Mean speeds within the lane shift were similar for the AWP as compared to the standard pavement marking.
- Mean exiting speeds were similar for the AWP as compared to the standard pavement marking.

I-90

Speeds at the I-90 test site were collected using sensors. Data were collected during daytime and nighttime dry conditions as well as during nighttime wet conditions through the months of August and September 2011. The sample sizes for the data collection ranged from 300 vehicles to 1,504 vehicles. The samples at the I-90 test site included speeds along the travel lanes for both the standard pavement marking and the AWP crossovers. A one-way analysis of variance was conducted to compare the speeds assuming a null hypothesis that stated that the mean speeds were similar for the AWP and the standard pavement marking sites. The analyses were conducted for daytime dry conditions, nighttime rain conditions, and nighttime dry conditions.

RESULTS

From the speed data obtained by LIDAR, video extraction, and sensors, the research team compared various samples for each of the five test sites. Mean speeds were particularly dependent on site geometry, conditions, and characteristics; therefore, samples would only be compared with other samples from the same site. The mean speeds, standard deviations, and mean differences were first calculated, followed by a statistical analysis using either t-tests or ANOVA. Table 8 displays a summary table of the speed data collected and analyzed for all five test sites.

Table 8. Summary of statistics for speeds.

Site	Light	Weather	Paint	Location	Mean Speed (MPH)	Standard Deviation	Mean Difference	P(T<=t) two-tail
I-85	Night	Rain	Standard	Entry Curve	44.9	5.2	1.4	0.009*
			Standard	Exit Curve	46.3	5.2		
US 15-501	Night	Rain	Standard	Entry Curve	38.7	6.2	3.5	< 0.001*
			AWP	Entry Curve	42.2	6.4		
US-421	Night	Rain	Standard	Entry Crossover	50.7	4.3	0.8	0.057
			AWP	Entry Crossover	51.5	4.6		
			Standard	Exit Crossover	56.7	5.2	-1.3	0.039*
			AWP	Exit Crossover	55.3	8.3		
			Standard	Entry Crossover	50.7	4.3	5.9	< 0.001*
			Standard	Exit Crossover	56.7	5.2		
			AWP	Entry Crossover	51.5	4.6	3.8	< 0.001*
			AWP	Exit Crossover	55.3	8.3		
US-32/33/50	Day	Rain	Standard	Entry Crossover	35.7	3.6	1.6	0.526
			AWP	Entry Crossover	37.3	6.4		
			Standard	Within Workzone	36.4	5.2	1.5	0.476
			AWP	Within Workzone	37.9	5.1		
			Standard	Exit Crossover	36.5	5.9	1.6	0.590
			AWP	Exit Crossover	38.1	5.8		
	Night	Rain	Standard	Entry Crossover	34.4	5.3	4.5	< 0.001*
			AWP	Entry Crossover	38.9	4.7		
			Standard	Within Workzone	37.2	4.8	0.6	0.982
			AWP	Within Workzone	37.8	5.5		
			Standard	Exit Crossover	38.6	4.2	-2.3	0.057
			AWP	Exit Crossover	36.3	5.0		
	Night	Clear	Standard	Entry Crossover	36.3	3.7	2.9	< 0.001*
			AWP	Entry Crossover	39.1	3.5		
			Standard	Within Workzone	37.8	4.1	0.3	0.997
			AWP	Within Workzone	38.1	3.5		
			Standard	Exit Crossover	39.3	5.1	-1.8	0.102
			AWP	Exit Crossover	37.6	3.5		
I-90	Day	Clear	Standard	Exit Crossover	52.8	8.3	4.0	0.714
			AWP	Entry Crossover	56.8	11.0		
	Night	Clear	Standard	Exit Crossover	55.9	9.8	-1.3	0.312
			AWP	Entry Crossover	54.6	8.7		
	Night	Rain	Standard	Exit Crossover	57.0	7.8	-5.0	< .001*
			AWP	Entry Crossover	52.1	10.1		

* p-value is statistically significant (α = 0.05)
1 mph = 1.6 kph

I-85

Speeds were compared between the entry and exit curves delineated with standard pavement marking at the northern crossover. The work zone speed limit was posted at 55 miles per hour (89 kph). Actual speeds at the northern crossover ranged from 44.9 to 46.3 miles per hour (72.3 to 74.5 kph). From the analysis, a higher mean speed was found for the exit curve. Furthermore, the p-value was statistically significant with 95 percent confidence. Speeds were likely lower than the posted speed limit because the site contained a single lane crossover with barriers on each side.

When comparing the speeds obtained from LIDAR speed guns, the northern crossover yielded a mean speed of 43.9 miles per hour (70.7 kph) based on a very limited sample size of 15, whereas the AWP (southern) crossover yielded a mean speed of 41.7 miles per hour (67.1 kph) using a sample size of 46. This resulted in a mean difference of 2.2 miles per hour (3.5 kph). From this limited analysis, drivers drove faster through the section with standard pavement marking than through the section with the AWP.

US-15/501

From the statistical analysis of the two samples obtained at US-15/501, mean speeds of 38.7 and 42.2 miles per hour (62.3 to 68 kph) were calculated for the standard pavement marking and the AWP entry curves, respectively. At a confidence interval of 95 percent, the mean speed of the AWP data was significantly greater (3.5 miles per hour, or 5.6 kph) than that of the standard pavement marking data. Both averages were noticeably lower than the posted speed limit of 45 miles per hour (72 kph).

US-421

The averages and standard deviations were calculated for the samples collected for each of the curves at the US-421 test site. The work zone speed limit was posted at 55 miles per hour (89 kph). Based on results from video data extraction, the mean speeds on each of the four crossovers ranged between 50.7 and 56.7 miles per hour (81.6 and 91.2 kph). Basic findings from entry and exit curves include the following:

- For both standard pavement marking curves and the AWP curves, the average speeds at the entry curves were lower than those of the exit curves.
- Average speeds on both entering curves were less than the posted speed limit.
- Average speeds on both exiting curves were just above the posted speed limit.
- Differences between the entering and exiting speeds were 3.0 to 6.0 miles per hour (4.8 to 9.7 kph).

More important are the results when comparing standard pavement marking and the AWP and the entry versus exit for each pavement marking type. The findings from this comparison at this site are the following:

- The entry curve speeds in the sections with the standard pavement marking were compared to those with the AWP. The mean speed was slightly greater than 1 mile per hour (1.6 kph) faster for the AWP. A p-value of 0.057 indicates that there was no statistically significant difference between speeds at the entry curves of both pavement markings, although the difference was practically significant (90+ percent confidence).

- In comparing the exit curves, the mean difference was just below 1.5 miles per hour (2.4 kph). Surprisingly, the exit curve with standard pavement marking had a higher mean speed than that with the AWP. The p-value calculated shows this finding to be significant with 95 percent confidence.

- Finally, when comparing entry and exit curves of the same pavement marking, there was a mean difference of at least 3.5 miles per hour (5.6 kph), again indicating drivers exit the work zone faster than when entering. Both t-tests give p-values much less than the significance level.

The findings from the entry and exit curve comparison support the findings from the I-85 test site, in which higher speeds were observed in the exit curve. In addition, although not statistically significant, the findings between standard and the AWP pavement markings at similar crossovers were comparable to the results from US-15/501.

US-32/33/50

The averages and standard deviations were calculated for the samples collected for each of the crossovers at the US-32/33/50 test site. The posted work zone speed limit was set at 55 miles per hour (89 kph). Based on results from video data extraction, the mean speeds ranged between 34.4 to 39.3 miles per hour (55.2 to 63.2 kph) for the various conditions—much lower than the posted speed limit. Substantial deviations from the posted speed limit can likely be attributed to the barriers present along the work zone, the single lane, and even the high visitor population that was not familiar with the roadway geometry.

Statistical tests were used to determine if the mean speeds of the AWP crossovers were significantly different from those of the standard pavement marking crossovers. The one-way analysis of variance was utilized to compare the mean speeds. Due to heterogeneous variances, the Welch's modification to the one-way analysis of variance was utilized, and the calculated F-value was based on an asymptotic distribution. In addition, due to the unequal variances and unequal sample sizes, the Games Howell post hoc test was utilized to examine specific differences within those samples tested in the one-way analysis of variance. Based on the one-way analysis of variance, it was determined that the mean speeds associated with the vehicles entering, within, and exiting the lane shift for the daytime rain, nighttime dry, and nighttime wet conditions were significantly different, as shown in table 9.

Table 9. US-32/33/50 speed ANOVA results.

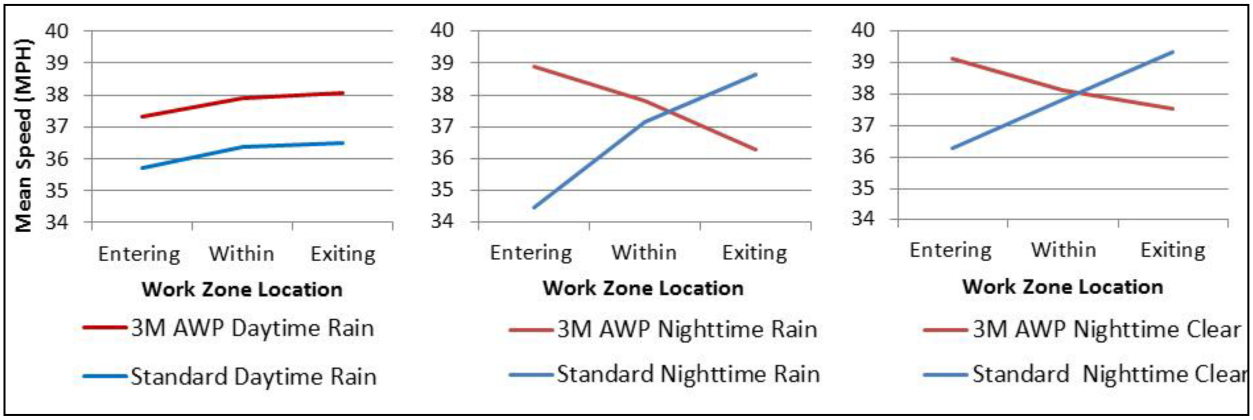
Comparison	Sum of Squares	Degrees of Freedom	Mean Squares	F-Calc	p-value
Daytime Rain Conditions					
Between Groups	328.57	5	65.713	2.843	0.17
Within Groups	14159.23	183.62	27.44		
Total	14487.79				
Nighttime Dry Conditions					
Between Groups	555.89	5	111.18	7.171	0.000*
Within Groups	7360.29	200.07	15.93		
Total	7916.17				
Nighttime Rain Conditions					
Between Groups	1044.29	5	208.86	8.696	0.000*
Within Groups	9870.81	411	24.02		
Total	10915.10				

* p-value is statistically significant ($\alpha = 0.05$)

For US-32/33/50, the ANOVA results indicated the following:

- The only statistically significant differences between the AWP and standard pavement marking were during nighttime dry and rainy conditions.
- Although not statistically significant, it is noteworthy that the AWP and standard pavement marking seem to have a large effect on speeds exiting the crossovers at nighttime dry and rainy conditions (p-values of 0.102 and 0.057, respectively).

Another trend is found when examining the data in a graphical visualization. As figure 25 shows, when plotting the data by location in the work zone (entry, within, and exiting) versus speed, it is evident that speeds generally increased through the work zone in all conditions except nighttime with the AWP.



1 mph = 1.6 kph

Figure 25. Graphs. US-32/33/50 speed results by location in work zone.

These findings suggest that the speed differential from entry to exit for the AWP is much more pronounced than with standard pavement marking, with a decreasing trend from the entrance through the exit. This also suggests that drivers are likely more confident entering the work zone with the AWP, as evidenced by the fact that speeds are higher during these two conditions than any other.

I-90

The averages and standard deviations were calculated for the samples collected for each of the two-lane crossovers at the I-90 test site. The posted work zone speed limit was set at 55 miles per hour (89 kph). Based on results from the sensor data extraction, the mean speeds ranged between 51.9 and 57.0 miles per hour (83.5 to 91.7 kph) for the various conditions. Average speeds on both two-lane crossovers were less than the posted speed limit for the AWP conditions, except for daytime, clear conditions. Average speeds during both the nighttime standard pavement marking conditions (clear and rain) exceeded the posted speed limit; however, the average speeds during the daytime clear conditions were less than the posted speed limit mainly due to the reduction of speeds through the work zone when workers were present, which continued through the end of the work zone.

Statistical tests were used to determine if the mean speed for the test site compared to the control site was statistically significant. Again, the one-way analysis of variance was utilized to compare the mean speeds. Due to heterogeneous variances, the Welch's modification to the one-way analysis of variance was utilized, and the calculated F-value was based on an asymptotic distribution. In addition, due to the unequal variances and unequal sample sizes, the Games Howell post hoc test was utilized to examine specific differences within those samples tested in the one-way analysis of variance. Based on the one-way analysis of variance, it was determined that the mean speeds associated with the vehicles traveling along the two-lane crossover for the three conditions were significantly different, as shown in table 10.

Table 10. I-90 speed analysis ANOVA results.

Comparison	Sum of Squares	Degrees of Freedom	Mean Squares	F-Calc	p-value
All Conditions					
Between Groups	21596.97	5	4319.39	51.32	0.000
Within Groups	522466.36	1849.71	87.93		
Total	544063.33				

* p-value is statistically significant ($\alpha = 0.05$)

For I-90, the ANOVA results provided earlier in table 8 indicated the following:

- The only statistically significant differences between the AWP and standard pavement marking were during nighttime rainy conditions.

- The mean speeds for those vehicles traveling along the two-lane crossover with the AWP were significantly lower than those vehicles traveling through the crossover with the standard pavement marking. However, unlike the US-32/33/50 site, the AWP was installed at an entry curve and the standard pavement marking was installed at an exit curve. Therefore, the difference in speeds at each crossover cannot be attributed solely to the pavement marking type, but could very likely be due to differences in entry versus exit curves. This is further validated by the findings at other sites with similar pavement markings at entry and exit curves, where major differences were noted between the two curves.

CONCLUSIONS AND RECOMMENDATIONS

Vehicle speed was used as a surrogate measure used to evaluate the safety performance of more reflective lane markings. From the analysis of the speed data, it is not clear what effect the more reflective pavement marking has on driver behavior, or if an increase or decrease in speeds is a positive effect. Nonetheless, knowing the changes in speeds due to the new pavement marking should be instructive.

Speeds should be analyzed with some caution, for their variability and dependence on a number of factors. In the case of this study, major factors affecting speeds included (1) the geometry of highway crossover, particularly lane shifts, (2) the installation of highway detours and the nature of work zones, (3) the intensity of rain, and (4) the lighting conditions. The research team attempted to compensate for these factors by keeping them consistent (when possible) when comparing various samples.

At the I-85 test site, two issues arose. The geometry varied slightly, and more importantly, the intensity of the rain likely varied since the crossovers were so far apart (6 miles, or 9.7 km). This being the case, it was unreasonable to compare the AWP curves with the standard pavement marking curves. Consequently, the team was only able to compare entry with exit curves for the standard pavement marking installation. At a 95 percent confidence level, the researchers found a slight increase in speed at the exit curve. One could assume that drivers likely decelerate entering the crossover and accelerate slightly exiting the crossover.

Data collection at the US-15/501 site used the same curve for analysis, thus keeping the highway geometry and work zone layout consistent. This issue that remained was the rain intensity, since data were collected during different rain events. Standard pavement markings were initially installed and video was taken. When enough rainy nighttime footage was recorded, the standard markings were overlaid with the AWP pavement markings. Therefore, it was impossible to get identical rain events, even if the monthly rainfall was consistent during data collection periods. Every attempt was made to get similar rain intensities using rain data obtained from the National Oceanic and Atmospheric Administration (NOAA).

From the footage used for analysis, the standard comparison sample was taken during a 2-hour period during which 1 inch (2.54 cm) of rain fell, whereas the AWP treatment sample saw just over 0.5 inches (1.27 cm) of rain for a 1 hour and 20 minute period, so the hourly rainfall intensities were very similar. Nonetheless, statistical analysis was used to compare the standard sample with the AWP sample. Speed was found to be higher on the AWP treatment sample. Even though average intensity was similar during both rain events, the researchers noted points of concern. First, the analysts observed consistent rainfall during the standard pavement marking data collection, while the rain intensity dramatically increased in the second half of the AWP data extraction. Second, possible changes in speed during phases of construction should be addressed. The standard comparison sample was collected just after the lane shift was constructed and opened as a detour. Even with familiar drivers, there can be an expected learning curve, thus decreasing maneuvering decision time and decreasing traveling speed until the mean speed could have returned to a steady state after the initial observation period.

The US-421 test site provided the most promising data from the North Carolina locations. Lane shift construction and opening was simultaneous as contractors worked to replace bridges on the four-lane divided highway. Both lane shifts had entry and exit crossovers side by side within a 0.5-mile (.8-km) stretch of highway. Therefore, the team was able to use synchronized video for data extraction and analysis. Some speed differences were noted when comparing the standard pavement marking curves with the AWP curves; however, the differences were small and conflicting (though statistically significant). For instance, when comparing pavement marking types at the entry curves, speeds were higher on the sections with AWP. This finding was not validated at the entry curves, where the standard pavement marking correlated with slightly higher speeds. Last, on both the AWP and standard pavement marking lane shifts, higher speeds were observed on exit curves than on entry curves.

The US-32/33/50 speed data analysis indicated that vehicles entering the lane shift utilizing the AWP during nighttime dry and rain conditions traveled at a higher rate of speed than on the lane shift utilizing the standard pavement marking. This is consistent with the theory that motorists will travel faster through a given length of highway due to the higher retroreflective pavement markings. On the other hand, the I-90 test site speed data analysis indicated that vehicles traveling through the two-lane crossover utilizing the AWP during the nighttime rain conditions traveled at a lower rate of speed as compared to the crossover utlizing the standard pavement marking. However, this finding at I-90 should be looked into further because both pavement markings were applied on different curves (entry and exit).

Overall, based on the comparisons between the mean speeds at the US-15/501, US-421, US-32/33/50, and I-90 test sites, the team finds no conclusive evidence that drivers travel faster through work zone detours delineated with the AWP than those with the standard pavement marking. There was no consistent positive or negative speed change between the two pavement marking types; in fact, the drivers on the AWP sections exhibited both higher and lower speeds than those on the standard pavement marking sections at each of the various crossovers studied.

In future studies, the research team recommends that speed data be collected by video extraction under the following circumstances:

1. Using synchronized video for highway curves similar in geometry and work zone layout.
2. Timing for speeds over a distance of at least 200 feet (61 m).
3. Calibrating measurements with supplemental speed gun recordings
4. Using larger samples sizes.
5. Removing outliers.
6. Developing macro-enabled databases for analysis.

LANE ENCROACHMENTS

AWP has been proven to be more retroreflective than standard pavement marking; however, the researchers found no conclusive evidence that speeds increased or decreased according to the type of pavement marking used. Taking a more direct approach, lane encroachments were used to evaluate the two pavement marking types. Lane encroachments are defined as vehicles that infringe upon the adjacent lane by crossing the center line striping of a multi-lane highway.

The research team examined lane encroachments at the North Carolina test sites only, as they had temporary lane shift detours installed during bridge construction projects.

DATA COLLECTION

Lane encroachment data were obtained through manual video extraction for two test sites in North Carolina. Once temporary detours (i.e., lane shifts) had been fully constructed and delineated with work zone pavement markings, the team set up video cameras to record highway activities at entering and exiting curves into and out of lane shifts. Video was recorded to a DVR from a high elevation to give the observer a clear overhead view of the lanes and lane lines. The team focused primarily on capturing rainy nighttime conditions for at least 2-hour periods. When sufficient video was recorded, the team took the equipment back to the lab for investigation and data extraction.

From the video, traffic volumes and lane encroachments were collected either for a total count or at 5-minute intervals. Traffic volumes were obtained simply by counting the number of vehicles passing a pre-designated segment of highway, whereas lane encroachments required additional effort. During nighttime conditions, lane lines were difficult to make out in the darkness of the videos. Therefore, the observer physically traced pavement striping from daytime footage and used these traces as lane line references for the nighttime footage. Lane encroachments were counted when a vehicle's tire crossed over a solid pavement stripe. Additionally, only the lead vehicle of a platoon was observed so as not to include vehicles simply following the lead vehicle's taillights.

STATISTICAL ANALYSIS OF LANE ENCROACHMENTS

I-85

This site was a single-lane crossover with barriers and RPMs; therefore, lane encroachment analysis was not conducted due to the quality of video and fact that this particular site was only a single lane (and thus had no second lane to encroach upon).

US-15/501

Multiple videos were recorded at a work zone crossover in 2009. Videos of nighttime, rainy conditions were shot on May 28 and July 12 between 11:00PM and 1:00AM and 9:00PM and 12:15AM, respectively. Additionally, the rainfall intensity was approximately 0.5 inches (12.7 mm) per hour for both recordings. Total vehicle counts and the number of vehicles that encroached lane lines were tallied. Although other video of nighttime rainy events were available, the lack of rain intensity and duration limited their use.

During the May video recording, standard pavement markings were installed. There were a total of 824 vehicles, of which 36 encroached. By the time of the July recording, the AWP markings had already been laid over the standard pavement markings. The AWP data had a total of 1,493 vehicles recorded, of which 30 encroached. Table 11 displays the summary table of lane encroachments.

Table 11. Chi-square results for US-15/501 lane encroachments.

Pavement Markings	Encroachments	Non Encroachments	Total
Standard	36	788	824
AWP	30	1463	1493
Total	66	2251	2317
		Chi Square (X^2)	10.68203

The percentages of vehicle encroachments were 4.6 percent and 2.1 percent for standard pavement marking and AWP markings, respectively. A Chi-square test indicated that the difference in lane encroachments for the AWP and standard pavement marking was statistically significant at the 99 percent confidence level. Therefore, the AWP appears to have reduced the percentage of lane encroachments at this crossover.

US-421

As noted earlier, at the US-421 test site there were lane shifts in both directions of the divided highway, both having very similar geometry. The westbound direction was treated with standard pavement marking while the eastbound direction was treated with the AWP. For each direction of travel, there were two crossovers (entry and exit). Each crossover contained entering and exiting curves. Therefore, at the US-421 site, there were a total of eight curves in which lane encroachments could occur—two per crossover, or four per direction. Lane encroachments were only taken for the lead vehicle of a platoon.

The team obtained 3.5 hours of video during rainy nighttime conditions concurrently at all of the curves. The actual vehicle counts were 2,582 for standard pavement marking (westbound direction) and 1,411 for the AWP (eastbound direction). There were 270 and 166 lead vehicle lane encroachments, respectively. Foreseeing the variability of traffic conditions, the observers recorded vehicle counts and lead vehicle encroachments at 5-minute intervals. Thus, 42 5-minute increments were obtained for nighttime, rainy conditions at each of the 4 crossovers.

Using the 5-minute samples of traffic volumes and lead vehicle encroachments, lane encroachment rates were calculated. The mean and standard deviations were computed from the samples of lane encroachment rates. Samples were compared, and their mean differences determined. Finally, t-tests were used to analyze the significance of various sample comparisons. The results of the t-tests were based on a 95 percent confidence interval.

When analyzing the lane encroachment rates, comparisons were made between standard pavement marking and the AWP. The comparisons were as follows:

- Standard pavement marking entry versus the AWP at an entry crossover.
- Standard pavement marking exit versus the AWP at an exit crossover.
- AWP at an entry versus an exit crossover.
- Standard pavement marking at an entry versus an exit crossover.
- Combined lane encroachment rates of standard pavement marking entry and exit versus rates of the AWP at entry and exit crossovers.

Table 12 summarizes the findings of the statistical tests.

Table 12. US-421 lane encroachment statistics.

	Statistical Analysis of Lane Encroachment Rates			
Sample Comparison	**Mean**	**Standard Deviation**	**Mean Difference**	**Two-tail p-value**
Standard Entry	4.1%	3.2%	+1.2%	0.1935
AWP Entry	5.3%	4.9%		
Standard Exit	6.4%	3.5%	+0.1%	0.8819
AWP Exit	6.5%	4.8%		
Standard Entry	4.1%	3.2%	+2.3%	0.0028*
Standard Exit	6.4%	3.5%		
AWP Entry	5.3%	4.9%	+1.2%	0.2591
AWP Exit	6.5%	4.8%		
Standard Entry + Exit	10.5%	5.4%	+1.3%	0.3571
AWP Entry + Exit	11.8%	7.5%		

* p-value is statistically significant ($\alpha = 0.05$)

Table 12 shows that crossovers marked with standard pavement marking had slightly lower encroachment rates than similar crossovers marked with the AWP. However, the differences were small, and based on the results from the t-tests no lane encroachment rate comparisons, except between standard pavement marking entry versus standard pavement marking exit, had statistically different rates.

CONCLUSION AND RECOMMENDATIONS

In North Carolina, the research team used lane encroachments as the primary factor to evaluate the safety measure of installing the brighter AWP. It was hypothesized that bright lane markings would enhance the driver's ability to clearly distinguish lanes on the roadway and make safer driving maneuvers. The results of the lane encroachment analysis provided inconclusive findings.

First, when studying the lane encroachments at the US-15/501 site, the results from the experimental test show that the installation of the AWP reduced the rate of lane encroachments by 50 percent. That is to say, the percentage of vehicles that encroached out of the total number of vehicles was half that of the percentage calculated for standard pavement markings. Upon first glance, this is impressive, yet it should be interpreted with caution. A variety of confounding issues may exist, especially regarding the variable nature of rain intensity. However, studying the rate of lane encroachments at the US-421 site, the team sought to compare differences between entry and exit curves installed with the AWP and standard pavement markings. T-tests showed that the small difference in lane encroachment rates were statistically insignificant.

Another interesting finding is the lane encroachment rates between entry and exit curves using the same pavement markings, which indicate that drivers are likely making more lane encroachments at the exit curves. Recalling findings from the speed analysis, there were similar statistically significant differences between entry and exit curves. Mean speeds were higher in exiting curves than in entry curves. The type of crossover appears to be more important to traffic operations than other factors studied.

LATERAL LANE PLACEMENT

Lane placement describes the distance a driver deviates laterally within the travel lane. Driver behavior and vehicle placement of vehicles travelling through the work zone was recorded using two methods of data collection: a video camera mounted in a survey vehicle and distance measuring sensors. The methodology for each data collection method is described in detail in the following sections.

DATA COLLECTION

Video Calculated Distances for US-32/33/50

To collect data on the lane placement of vehicles through the work zone for the US-32/33/50 site, a digital video camera was mounted inside a survey vehicle and data were recorded through the advance warning area and through the shift area of the work zone while following a target vehicle in the traffic stream. Due to the remote location of the site and the lack of ambient lighting, video data collection from an elevated location was not feasible because the video could not delineate the pavement markings. Therefore, motorists were followed through the work zone and monitored through the use of a video camera on-site. The motorists were not aware that they were being monitored and, thus, their driving behavior was unbiased.

The video data were then analyzed in the laboratory to obtain quantifiable lateral lane placement data for each observed vehicle. When analyzing the video data, the lateral placement was determined by locating the center of the lane and comparing that location to the location of the center of the vehicle's license plate in a 6-inch positional alignment. When a vehicle was positioned left of the centerline, or away from the work zone, that was recorded as a positive distance, whereas a vehicle traveling right of the centerline, or closer to the work zone, was recorded as a negative distance. The data were extracted from the video for every second of travel through the shift and immediately before and after the shift.

Distance Measuring Sensors for I-90

To obtain lateral placement distances of vehicles traveling through the I-90 crossovers, sensors were utilized to collect data from the shoulder of the roadway. These sensors were the same used for speed collection.

For the I-90 test site, the lane placement and speed data were collected for the double-lane crossover sections of the work zones for each pavement marking type. For the crossover section with the AWP treatment, four sensors were placed along both of the travel lanes in the middle of the crossover. The sensors were placed along the left travel lane at 100-foot (30.5-m) spacing, with the first sensor placed at approximately the point of reverse curvature in the double-lane crossover. The last sensor on the right travel lane was placed just prior to the jersey barriers dividing the eastbound and westbound lanes. The remaining sensors were then placed at 100-foot (30.5-m) spacing back from the last sensor. For the standard pavement marking treatment, data could not be feasibly collected for the left travel lane, as there was no shoulder available alongside the lane. As a result, all eight sensors were placed along the right travel lane at 100-foot (30.5-m) spacing, with the first sensor located approximately 200 feet (61 m) into the double-lane crossover. Due to the potential in comparing lane placement and speed data for left and right lanes, a statistical analysis was conducted to determine differences, if any, between the two lanes for one direction of travel. The results from the ANOVA indicated that there was no statistical difference between lane placements or speeds between the left and the right lane. Therefore, comparisons can be made between the pavement marking sites.

For each of the work zones studied, the sensors were oriented perpendicular to the roadway and placed on the graded shoulder. The distance from the sensor to the edge line of the closest travel lane was measured and recorded to determine the lane placement of the vehicle. The sensors were placed within 6 feet (1.8 m) of the edge line to remain within the operating range of the sensors. The primary focus was to be able to detect a vehicle within the travel lane adjacent to the shoulder where the sensors were located. Once all of the sensors were in place, the synchronized sampling was conducted using the MicroStrain Node Commander® software installed on a laptop computer. The synchronized sampling was conducted for the eight sensors at a rate of 128 Hz. The data were collected for approximately 1.5 to 2 hours, depending on the life of the laptop's battery.

ANALYSIS METHODOLOGY

Statistical analyses were conducted for the lateral lane placement data collected at the two Ohio sites. Averages and standard deviations were calculated from the filtered lateral placement data. The data were compared using the one-way analysis of variance testing the significance at a 95 percent level of confidence.

RESULTS

The primary difference between the two test sites was that the distances of lane placements were relative to different reference points, and therefore incomparable. At US-32/33/50, the distances were taken for lane placement relative to the center of the travel lane, whereas at I-90 distances were measured from the shoulder perpendicular to the travel way. The mean speeds, standard deviations, and mean differences were first calculated, followed by a statistical analysis using either t-tests or ANOVA for sample comparison. Table 13 displays a summary table of the lane placement data collected and analyzed for the test sites, followed by a section summarizing the findings from each site studied.

US-32/33/50

The averages and standard deviations were calculated for the samples collected for each of the lane shifts at the US-32/33/50 test site. Based on results from video data extraction, the mean lateral lane placements ranged between 0.043 to 0.771 feet (1.3 to 23.5 cm) from the center of the lane. The positive nature of each of the means indicates that motorists were traveling to the right of the center of the lane, or veering away from the work zone.

Statistical tests were used to determine if the mean lateral lane placement for the test site as compared to the control site was statistically significant. The one-way analysis of variance was utilized to compare the mean speeds. Due to heterogeneous variances, the Welch's modification to the one-way analysis of variance was utilized, and the calculated F-value was based on an asymptotic distribution. In addition, due to the unequal variances and unequal sample sizes, the Games Howell post hoc test was utilized to examine specific differences within those samples tested in the one-way analysis of variance. Based on the one-way analysis of variance, it was determined that the mean lateral lane placements associated with the vehicles entering, within, and exiting the lane shift for the daytime rain, nighttime dry, and nighttime wet conditions were significantly different, as shown in table 14.

Table 13. Summary of statistics for lateral lane placement.

Site	Light	Weather	Paint	Location	Average Lane Placement (Feet)	Standard Deviation	Mean Difference	P(T<=t) two-tail
US 32/33/50	Day	Rain	Standard	Entry Crossover	0.61	0.46	0.15	0.214
			AWP	Entry Crossover	0.75	0.43		
			Standard	Within Work Zone	0.28	0.31	0.15	0.017*
			AWP	Within Work Zone	0.43	0.40		
			Standard	Exit Crossover	0.55	0.35	-0.50	< 0.001*
			AWP	Exit Crossover	0.04	0.46		
	Night	Rain	Standard	Entry Crossover	0.57	0.46	0.09	0.765
			AWP	Entry Crossover	0.66	0.39		
			Standard	Within Work Zone	0.29	0.39	0.21	0.001*
			AWP	Within Work Zone	0.50	0.39		
			Standard	Exit Crossover	0.57	0.41	-0.33	< .001*
			AWP	Exit Crossover	0.24	0.47		
	Night	Clear	Standard	Entry Crossover	0.52	0.54	0.25	0.003*
			AWP	Entry Crossover	0.77	0.45		
			Standard	Within Work Zone	0.30	0.31	0.23	< 0.001*
			AWP	Within Work Zone	0.53	0.42		
			Standard	Exit Crossover	0.67	0.40	-0.28	0.001*
			AWP	Exit Crossover	0.39	0.40		
I-90	Day	Clear	Standard	Exit Crossover	3.25	4.42	2.57	< 0.001*
			AWP	Entry Crossover	5.82	3.75		
	Night	Clear	Standard	Exit Crossover	9.28	2.13	-3.80	< 0.001*
			AWP	Entry Crossover	5.48	3.03		
	Night	Rain	Standard	Exit Crossover	6.57	3.09	-0.07	0.994
			AWP	Entry Crossover	6.50	3.01		

* p-value is statistically significant (α = 0.05)
1 foot = 30.5 cm

Table 14. US-32/33/50 lane placement ANOVA results.

Comparison	Sum of Squares	Degrees of Freedom	Mean Squares	F-Calc	p-value
Daytime Rain Conditions					
Between Groups	25.02	5	5.00	29.148	< 0.001*
Within Groups	88.49	240.03	0.159		
Total	113.51				
Nighttime Dry Conditions					
Between Groups	15.12	5	3.025	20.854	< 0.001*
Within Groups	109.61	257.84	0.184		
Total	124.73				
Nighttime Rain Conditions					
Between Groups	12.67	5	2.535	14.259	< 0.001*
Within Groups	97.00	251.25	0.174		
Total	109.68				

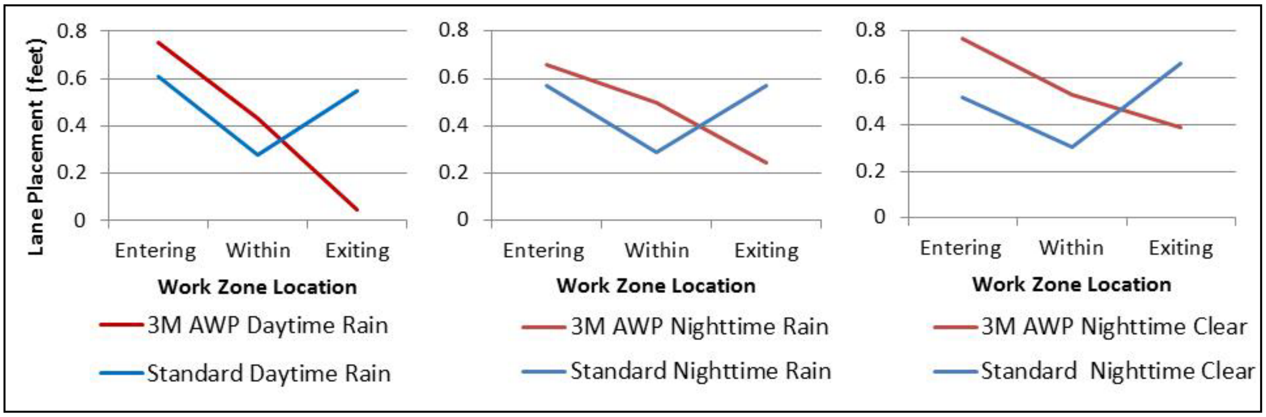
* p-value is statistically significant (α = 0.05)

For US-32/33/50, the ANOVA results provided in tables 13 and 14 indicate that for all conditions:

- For daytime and nighttime rain conditions, the mean lateral lane placements within and exiting the lane shifts were statistically different between the standard pavement marking and the AWP, while means for entering the lane shift were statistically similar. While traveling through the work zone, vehicles tended to maintain a position closer to the white markings when utilizing the AWP. When exiting the work zone, vehicles maintained a position closer to the center of the lane delineated with the AWP.

- For the nighttime dry conditions, the mean lateral lane placements for all locations along the lane shifts were statistically different between the standard pavement marking and the AWP sections. When entering the lane shift and through the lane shift, those vehicles traveling through the AWP work zone maintained a position closer to the white pavement markings as compared to the standard pavement marking work zone. When exiting the work zone, vehicles traveling through the AWP work zone were able to maintain a position closer to the center of the lane than those traveling through the standard pavement marking work zone.

The US-32/33/50 results are visually represented in figure 26.



1 foot = 30.5 cm

Figure 26. Graphs. US-32/33/50 lane placement results.

I-90

The averages and standard deviations were calculated for the samples collected for each of the two-lane crossovers at the I-90 test site. The sensor was placed 3 feet (.91 m) away from the outside edge of the lane line. Based on results from sensor data extraction, the mean lateral lane placements (i.e., the distance between the sensor and the vehicle's closest tire) ranged between 3.25 and 9.28 feet (1 and 2.8 m). Given a lane width of 12 feet (3.7 m) and an assumed vehicle width of 7 feet (2.1 m), a vehicle positioned directly in the center of the lane would be 2.5 feet (.76 m) inside the edge lane. Therefore, a vehicle position (the edge of the vehicle) that was approximately 5.5 feet (3 + 2.5 feet), or 1.7 meters, from the sensor is assumed to be located within the center of the closest lane in the two-lane crossover. A vehicle detected 9.28 feet (2.8 m) from the sensor is assumed to be encroaching a total of 1.28 feet (0.39 m) in the second lane as follows: the near tire is 6.28 feet (1.91 m) from the near edge line (9.28 feet – 3 feet set back for the sensor), with the far tire positioned 13.28 feet (4.05 m) from the near edge line (6.28 feet + 7-foot width). Based on a 12-foot (3.7-m) lane width, the far tire is located 1.28 feet (0.39 m) inside the adjacent lane.

Table 15 shows a summary of lane placements determined for I-90. Based on the one-way analysis of variance, it was determined that the mean lateral lane placements associated with the vehicles traveling through the two-lane crossover for the daytime dry, nighttime dry, and nighttime wet conditions were significantly different, as shown in table 15.

Table 15. I-90 lane placement ANOVA results.

Comparison	Sum of Squares	Degrees of Freedom	Mean Squares	F-Calc	p-value
All Conditions					
Between Groups	22505.34	6	3750.89	341.09	< 0.001*
Within Groups	176294.20	3855.34	12.56		
Total	198799.54				

* p-value is statistically significant (α = 0.05)

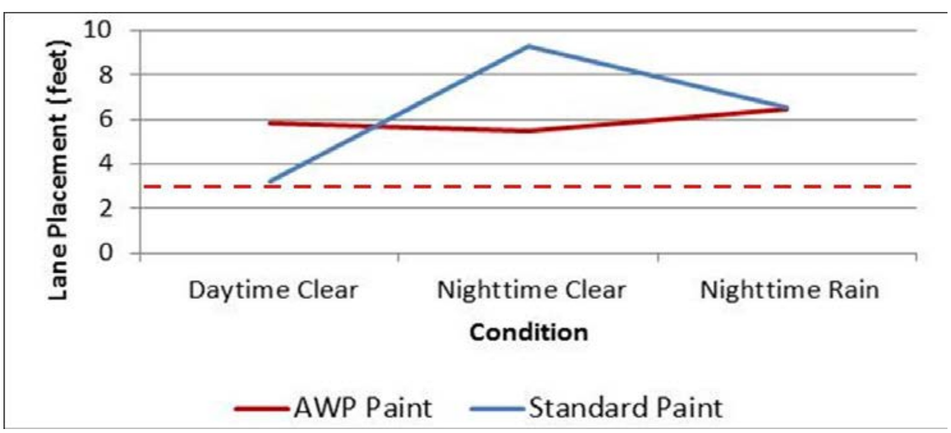
For I-90, the ANOVA results indicate the following:

- During daytime dry conditions, the mean lateral lane placements of vehicles on the standard pavement marking and the AWP sections were statistically different. The vehicles traveling through the AWP crossover generally maintained a position in the center of the travel lane more consistently than those traveling along the standard pavement marking crossover. The edges of vehicles traveling along the standard pavement marking crossover were generally located just 1 foot (.3 m) from the white lane line.

- For the nighttime dry conditions, the post hoc analysis also indicated that the vehicles traveling through the AWP crossover were able to maintain a position in the center of the lane more consistently than those traveling along the standard pavement marking crossover. The edges of vehicles traveling along the standard pavement marking crossover were generally located closer to the lane line dividing the two lanes, thereby creating a sideswipe crash potential.

- The post hoc conditions indicated that, during the nighttime rain conditions, the lateral lane placement of vehicles were statistically similar.

The I-90 results in table 15 are visually represented in figure 27.



1 foot = .3 m

Figure 27. Graph. I-90 lane placement results.

Note: The dashed line represents the distance from the sensor to the edge of the outer lane line. The lane placement measurements are the linear distance between the sensor and the vehicles closest tire.

CONCLUSIONS

The lateral lane placement of vehicles was quantified to assess the ability of the pavement markings in guiding motorists through the work zone. Vehicle placement within a work zone was considered a primary measure for safety due to the ability to discern a vehicle's crash risk. The crash risk was identified by the location of a vehicle close to a lane line, indicating the potential for a sideswipe crash or intrusion into the work zone, increasing the potential for a fixed object crash or a pedestrian crash.

Along the US-32/33/50 site, motorists maintained their position either in the center of the lane or close to the white edge marking. Statistical differences were noted for the daytime and nighttime rain conditions within and exiting the lane shift and for all the locations for the nighttime dry condition. Generally, when exiting the lane shift, those vehicles traveling through the AWP site were able to maintain a position closer to the center of the lane than those traveling through the standard pavement marking site.

For the I-90 site, motorists also maintained their position in the center of the lane when traveling through the AWP site for the daytime dry and nighttime dry conditions. During the nighttime rain conditions, motorists maintained their position nearly in the center of the lane for both the AWP and the standard pavement marking sites. While traveling through the standard pavement marking site during the nighttime dry conditions, the mean lateral lane placement position of the vehicles indicated a higher potential for sideswipe crashes.

It was preferable for motorists to be able to locate their vehicle in the center of the lane to minimize the crash potential. However, based on the higher levels of retroreflectivity associated with the white pavement markings, it was not surprising that drivers would utilize the white edge line to appropriately position their vehicles. At the I-90 site, the examined lane for lateral placement utilized white pavement markings along both sides of the lane, which enabled drivers to maintain their lane appropriately more frequently.

OVERALL CONCLUSIONS

This research effort sought to quantify the effects of a new pavement marking product developed by 3M for work zone deployment under nighttime rainy conditions. The AWP was previously tested under rain simulated conditions, and findings indicated that the marking was much more visible than its conventional counterpart, primarily due to supplemental optical elements that retroreflect light in rain conditions. This research study builds on these findings by employing studies at actual work zones. Four MOEs were utilized in studying five work zones in North Carolina and Ohio. These MOEs included retroreflectivity, speed, lane encroachment, and lateral lane placement.

Retroreflectivity measurements were taken to determine 1) differences in AWP applications across sites and 2) differences between AWP and standard pavement marking at each individual site. From the data, it can be concluded that AWP applications had statistically significant differences between the AWP and standard pavement marking; however, there was not consistency among the pavement marking contractors in the application of either pavement marking type. This suggests that pavement marking contractors likely have different application methods with very little consistency in application rates and element drop rates. The research team suggests that future studies look at the retroreflectivity values over time to see the degradation rates of individual pavement markings under actual field conditions.

Speed was utilized to supplement findings regarding lateral lane placement. The research team used speed as a supplemental finding because higher or lower speeds through work zones proved not to be a good indicator of improved safety. For instance, increased visibility may result in increased speed if there is more driver comfort. It is not known what affect this may have on driver safety. Nevertheless, analyses of speeds were instructive and interesting. Speeds should be interpreted with caution due to their variability and dependence on many factors, primarily the geometry of the crossovers being compared, rain intensity during different analysis periods, method of extraction, and overall light conditions. The research team took every possible measure to eliminate as much variability as possible when collecting data and making comparisons.

Speeds were analyzed at all five work zone sites. The overall findings indicated the following:

- Statistically significant differences in speeds at entry and exit portions of a single crossover. This indicates that drivers tend to decelerate into each crossover and speed up exiting the same crossover, regardless of the marking type used.
- Statistically significant differences in speeds at entry and exit curves (entering and exiting the entire work zone – two crossovers). The findings showed that drivers drive 3.8 to 5.9 miles per hour (6.1 to 9.5 kph) faster when exiting the work zone.
- Although inconclusive, it appears that speeds were more likely to be higher in similar entry or exit curves when AWP was used than when standard pavement marking was used. This was the case in three of four different sets of curves that were compared, and all were statistically significant except one. For all practical purposes, even this one sample was significant (p-value =0.057).

Lane encroachment and lateral lane placement were the primary MOEs used to determine if safety had improved using the new AWP, as these measures are easily correlated with driver's lane-keeping ability. It was hypothesized that brighter lane markings would enhance the driver's ability to distinguish lanes on the roadway and make safer driving maneuvers. A total of four sites were studied for lane-keeping, two each for lane encroachments and lateral lane placement.

Lane encroachments were defined as vehicles crossing the lane line in a crossover. Comparing both pavement marking types in similar curves provided contrasting findings. The first site studied indicated that a higher number of lane encroachments occurred at standard pavement marking curves; however, that study introduced several factors that could not be accounted for directly (such as rain intensity). The second study, which was more robust, found statistically insignificant findings that standard markings resulted in more lane encroachments than AWP.

An interesting finding did emerge at these two sites when comparing entry and exit curves for both marking types—the exit lane was found to have more lane encroachments. This correlates to earlier findings that speeds were higher at exit curves (3.5 miles per hour [5.6 kph] or greater). This finding indicates that more attention should likely be given to the exit curve of a work zone since higher lane encroachments and speeds likely lead to higher potential for a serious collision.

Lateral lane placement describes a vehicle's proximity to a lane line, indicating the potential for a conflict or crash. Two sites were studied, one comparing an entry, within, and exit portions of two parallel work zones and the other comparing the entry and exit crossover for one direction of travel. At the first site, statistically significant differences were noted for daytime and nighttime rainy conditions within and exiting the lane shift; drivers maintained their lateral placement better within a work zone marked with standard markings but maintained their lateral placement better when exiting a work zone marked with AWP. During nighttime clear conditions, drivers maintained their lateral placement better throughout work zones marked with standard markings, while a statistically significant improvement in lateral lane placement was found with AWP when drivers were exiting the work zone.

At the second site, results also varied. During daytime clear conditions, drivers in the standard pavement marking sections maintained their lateral placement better. In contrast, during nighttime clear conditions, they maintained their lateral placement better in the sections marked with AWP. More importantly, nighttime rain conditions showed no statistically significant difference between the pavement markings.

In short, findings for lateral lane placement were similar to those regarding lane encroachments. Findings varied among sites and locations within the work zone; therefore, the findings were inconclusive.

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