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THE BENEFITS OF PAVEMENT MARKINGS: A RENEWED PERSPECTIVE BASED ON RECENT AND ONGOING RESEARCH

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ABSTRACT
One of the most important aspects of a safe and efficient roadway is the uniform application of pavement markings to delineate the roadway path and specific traffic lanes. Pavement markings can communicate information to road users like no other traffic control device. They provide continuous information to road users related to the roadway alignment, vehicle positioning, and other important driving-related tasks.

It is estimated that in the United States alone, approximately $2 billion is spent annually on pavement markings. Despite these annual expenditures, there is a general void in terms of a consolidated effort that attempts to quantify proven benefits of pavement markings. Over the years, many research projects have focused on specific elements of pavement markings. This paper was developed to bring together many of the recent and ongoing research efforts to demonstrate a renewed perspective regarding the benefits of pavement markings and, where information is available, describe the benefits of various aspects of pavement markings. This paper presents areas where conclusive findings are available, and describes areas where findings are available but show inconsistent and sometimes conflicting results.

INTRODUCTION

Pavement markings play one of the most important safety functions on our roads. They are widely accepted as being beneficial to drivers in that they communicate the intended travel path for short-range operations and the roadway alignment for long-range delineation. To ensure consistent application of pavement markings, their characteristics and warranting criteria are described in the *Manual on Uniform Traffic Control Devices* (MUTCD) (*1*), setting national standards on their application.

Despite the national pavement marking standards described in the MUTCD, according to a recent American Association of State Highway and Transportation Officials (AASHTO) report, every 21 minutes a highway death occurs as a result of a lane departure. In total, that is over 25,000 fatalities per year, or almost 60 percent of the nation's highway fatalities. AASHTO has developed a Strategic Highway Safety Plan that is designed to reduce these numbers (*2*). The very first objective of the AASHTO Safety Plan is to keep vehicles in their lanes and on the road.

The AASHTO Safety Plan includes a list of 22 goals to reduce highway fatalities. Various states around the country that have implemented the AASHTO Safety Plan have reported successes. . For instance, for the last three years, the Missouri Department of Transportation has focused on lane departure countermeasures. They have implemented the following countermeasures, which have led to a 25 percent reduction in lane departure fatalities from 2005 to 2007:

- edge lines and centerlines on all major highways, as well as minor highways with a history of crashes;
- 6-inch pavement marking edge lines and skip lines on all major highways;
- 4-foot shoulders on major highways;
- guardrail and median barriers on all major highways; and
- signing improvements.

AASHTO's first objective—keeping drivers on the road—appears simple enough. However, the safety potential of the objective is largely unknown. Surprisingly, there is an apparent lack of information concerning the most effective manner for keeping drivers on the road. Obviously, pavement markings are a big part of the equation. Although other safety treatments can also be used to keep drivers on the road, this paper is exclusively dedicated to pavement markings and their potential contribution towards increasing highway safety.

ANNUAL PAVEMENT MARKING EXPENDITURES

The science and effort dedicated to pavement markings can sometimes be overlooked. Perhaps this is a function of pavement marking unit costs, typically presented in cents per foot on the order of \$0.10 to \$0.25 per foot for conventional markings. However, when each marking on a highway and each mile of a highway are added up, the annual cost of pavement markings in the United States can be surprising. In an effort to estimate the annual costs, several sources of state agency information were combined to develop an estimated annual cost of pavement markings. The estimate is based on data from 18 states making up 45 percent of the state-maintained highway miles in the United States (*3*). Extrapolating the average cost per mile for the remaining 32 states produced a total annual pavement marking estimate of \$911 million in 2007. However, this does not include local roads, toll authorities, or private roads and other facilities such as parking lots and airports. Nationwide, local roads account for about 75 percent of the nation's highways and roads, or 2.93 million miles (of which about 1.65 million are paved) (*4, 5*). While many of these roads are probably not marked (there are no data at this level), there is undoubtedly a substantial proportion that are marked. Given the miles of local roads and other facilities that use pavement markings, the annual state pavement marking expenditure was doubled and rounded, resulting in a nationwide annual pavement marking expenditure of approximately $2 billion in 2007.

BENEFITS OF PAVEMENT MARKINGS

Despite these annual expenditures, there is a general void in terms of a consolidated effort that attempts to quantify proven benefits of pavement markings. Over the years, many research projects have focused on specific elements of pavement markings. This paper discusses and references early landmark studies, but an emphasis has been placed on some of the more recent studies because significant strides have been made to identify pavement marking benefits. Many of these recent studies have been the beneficiary of advanced technologies that allow for innovative research methodologies. When combined with lessons learned from previous research, the most recent research offers new insights into the benefits of pavement markings that were previously undetectable. This paper was developed to bring together many of the recent and ongoing research efforts to demonstrate a renewed perspective regarding the benefits of pavement markings and, where information is available, describe the benefits of various aspects of pavement markings. This paper presents areas where conclusive findings are available, and describes areas where findings are available but show inconsistent and sometimes conflicting results.

Ideally, this paper would focus exclusively on crash studies and cost-effectiveness studies. As described earlier, however, there is not an exhaustive amount of safety-related information on pavement markings. In lieu of safety data, other measures of effectiveness have been used to assess the benefits of pavement markings. This paper describes four common measures of pavement marking performance: safety studies, subjective evaluations, vehicle operational studies, and visibility-related studies. Uncommon or unique measures of performance are also described.

PAVEMENT MARKING SAFETY STUDIES

Many agencies are experimenting with enhanced pavement markings to reduce crashes and/or crash rates (i.e., adding markings to rural two-lane highways, adding wider edge lines, installing specially designed wet markings, etc.). Much of this emphasis has resulted from national programs such as AASHTO's Safety Plan as described earlier. Other factors, such as increased emphasis on accommodating older drivers, have also inspired agencies to evaluate their marking programs.

Some studies have suggested that the use of markings plays a role in the reduction of specific crash types under certain conditions (*6, 7, 8*). Run-off-road and opposite-direction crashes are generally overrepresented on our nation's highways, especially on horizontal curves and at night, when fatal crashes are three to four times more likely to occur. In addition, due to visual and cognitive deficiencies, older and impaired drivers are especially susceptible to these types of crashes. Therefore, crash types that are most likely affected by added markings or enhanced markings (added width or more retroreflectivity) are run-off-road and opposite-direction crashes that occur at night, occur on curves, and involve drivers with reduced visual or cognitive capabilities (e.g., older drivers or impaired drivers).

Early Pavement Marking Safety Studies

The earliest research shows consensus that edge line markings provide crash reductions versus no markings at all. For instance, in 1957 a study was initiated to install edge lines on rural two-lane highways that were at least 20 feet wide (*9*). A before-after crash study showed a 19 percent reduction in crashes after the installation of the edge lines. In addition, edge lines resulted in a 37 percent reduction in fatalities and injuries, a 63 percent reduction in crashes at access points such as intersections and driveways, and a 35 percent reduction in nighttime crashes. Similarly, another study initiated in 1959 showed that adding edge lines on rural two-lane highways 20 to 26 feet wide and with a minimum average daily traffic (ADT) of 1,000 vehicles per day (vpd) resulted in a 78 percent reduction in fatalities and a 46 percent decrease in the number of crashes at access points (*10*).

Probably one of the most robust studies to date concerning the safety benefits of adding pavement markings (edge lines in this case) was conceived from the Highway Safety Act of 1973, which established specific highway safety improvement programs including a pavement marking demonstration program that provided 100 percent federal funding for pavement markings on all highways excluding the Interstate Highway System (*11*). The Surface Transportation Assistance Act of 1978 continued funding for the program through fiscal year 1981.

Although 38 states participated in the demonstration program effort, data from only six states met the minimum criteria for a focused study on pavement marking benefits (resulting in 225 study sites). The minimum criteria for the study sites were that they had to be on two-lane highway sections at least 5 miles in length, have a pavement width of at least 16 feet, have a speed limit of at least 40 mph, and have no other safety improvements except adding pavement markings. The statistical approach used daytime crashes as a control mechanism for regression to the mean. Property damage only (PDO) crashes were not used, and fatal and injury crashes were combined.

Overall, there was a statistically significant 12 percent decrease in nighttime crashes. Adding edge lines resulted in a statistically significant 16 percent decrease in nighttime crashes and a statistically significant 33 percent decrease in low-visibility nighttime crashes.

The results also showed that adding centerlines and edge lines, and adding edge lines to roadways that previously only had centerlines, was most effective on roadways in mountainous and rolling terrain. The reduction in both nighttime and low-visibility nighttime crashes was statistically significant for both mountainous and rolling terrain.

When considering pavement width, several insightful findings appeared. For instance, 22-foot pavements exhibited a 36 percent reduction in nighttime crash rates and a 52 percent reduction in low-visibility nighttime crashes (when edge lines were added to existing centerlines or both centerlines and edge lines were added). For the same group of roadways and for 20-foot pavements, there was a statistically significant 13 percent decrease in nighttime crashes and a statistically significant 23 percent decrease in low-visibility nighttime crashes. For pavement widths of 18 feet or less, there was a statistically significantly 46 percent decrease in low-visibility nighttime crashes.

The report shows that adding edge lines to existing two-lane roadways with centerlines is a cost-effective crash-reducing treatment. A detailed example of North Dakota's edge line program shows a benefit-cost (B/C) ratio of 23:1, despite an increase in PDO crashes.

More Recent Pavement Marking Safety Studies

Much has changed since the first pavement marking studies, including vehicle design, vehicle speeds, and traffic volumes. A more recent study, and one of the most often cited pavement marking safety studies, was published by Miller in 1991 (*12*). Using crash statistics and cost estimates from that time, Miller determined that even on rural two-lane roads with an ADT as low as 500 vpd, edge lines yield a B/C ratio of 17:1. On average, Miller showed a B/C ratio of 60:1, noting that the B/C ratio increases with traffic volumes and the urban ratio is twice the rural ratio. Miller further concluded that edge lines would be justified on two-lane rural roadways if an average of one non-intersection crash occurs annually every 15.5 miles.

Miller included a meta-analysis of studies with pavement marking safety numbers. He found, using studies deemed credible, an average crash reduction of 21 percent that could be attributed to pavement markings. One of the reports he reviewed was by Bali et al. (*13*), who examined delineation treatments on rural two-lane highways. This was a 10-state study including more than 500 sites. Their study found that adding edge lines and centerlines reduced crashes by 36 percent. Adding edge lines to existing centerlines reduced crashes by 8 percent. Using the Bali et al. data, Miller produced a B/C ratio for adding edge lines to rural two-lane highways as a function of ADT (see Figure 1).

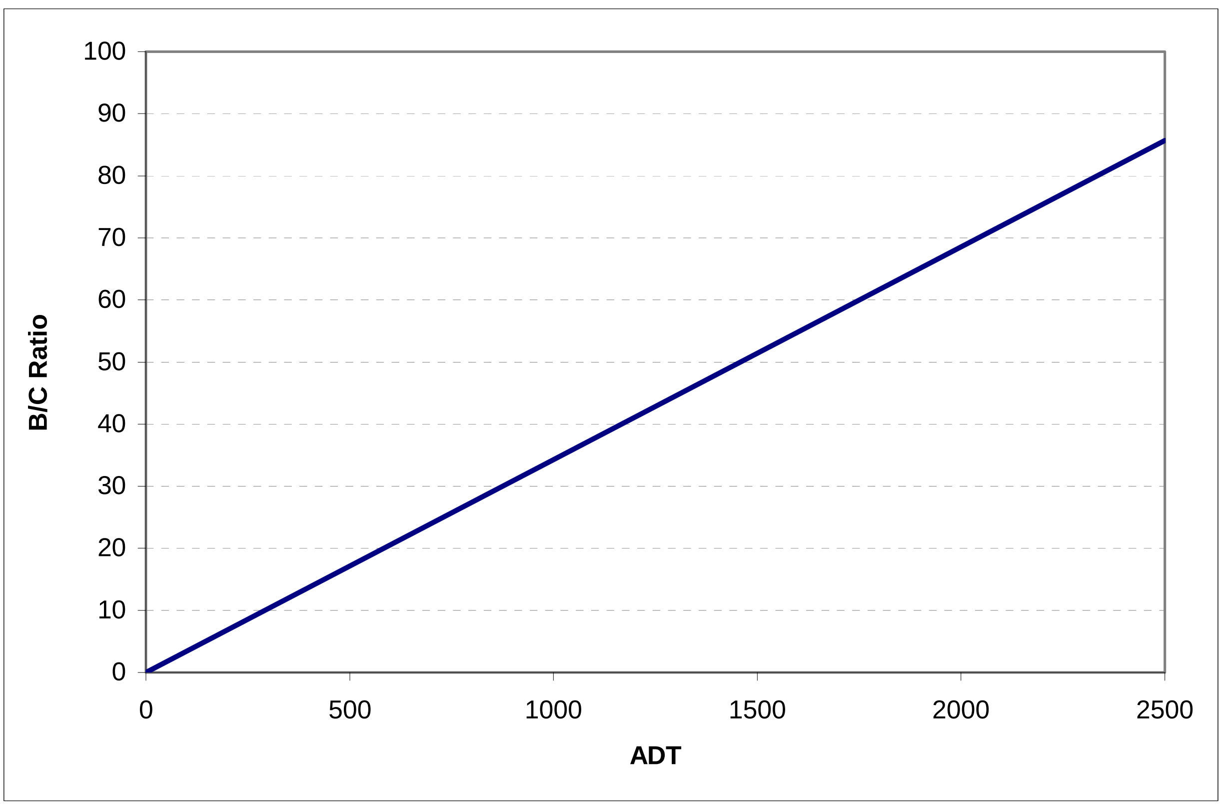

FIGURE 1 Benefit-Cost Ratio for Adding Edge Lines on Two-Lane Highways.

Even more recently, several meta-analysis efforts have focused on estimating crash reduction factors expected for specific countermeasures. These documents include comprehensive literature reviews for various pavement marking applications by factors such as crash type, crash severity, and lane volume (*14, 15*). A summary of crash reduction factors for various pavement marking countermeasures is shown below.

Countermeasure	Crash Reduction Factor
• Install lane lines to multilane urban roads	18
• Install centerlines	–1 to 36
• Install centerlines and edge lines	–3 to 24
• Install edge lines	4 to 66

Safety of Wider Pavement Markings

Naïve before-after crash studies conducted in Virginia and New Mexico in 1987 and 1988 suggest that wider lines have no safety benefit in terms of reducing crashes (*6, 16*). However, these studies were hampered by insufficient data and lack of experimental control. In an ongoing Federal Highway Administration (FHWA) study, commenced in 2006, researchers are taking a much more extensive look at the safety of wider pavement markings (*17*). As part of the current study, a nationwide survey was conducted to identify states that have wider pavement markings (wider than 4 inches) on all or some of their highways. For those states using wider pavement markings, follow-up phone surveys were used to determine if:

- the locations (by route number and linear reference) could be determined;
- the use was extensive on roadway segments (i.e., not small spot treatments);
- the date of installation was known; and
- sufficient crash, traffic, and roadway data existed.

The convergence of all the necessary criteria was rare, but three states were identified as having the required information—Michigan, Illinois, and Kansas. To date, the researchers have focused their efforts on rural two-lane highways in Illinois and Michigan. The total numbers of crashes by severity along with single-vehicle and opposite-direction crashes have been disaggregated by time of day, driver age, and weather. The widespread use of wider lines in these states minimizes the concern of selection bias or regression to the mean.

In Illinois, data screening reduced the rural two-lane data set to 3,973 segments (1,817 miles) consisting of 3,224 segments (1,511 miles) with 4-inch edge lines and 749 segments (306 miles) with 5-inch edge lines.

TABLE **1** shows the estimates of the negative binomial regression model coefficients. The regression coefficient for edge line width was negative and statistically significant at $\alpha = 0.05$, which indicates a positive safety effect of wider edge lines (i.e., a smaller number of crashes is associated with wider edge lines). It can also be observed that the signs of the coefficients for lane width, shoulder width, log of annual average daily traffic (AADT), and presence of horizontal curve (whenever they are statistically significant) are consistent with intuition.

TABLE 1 Estimates of Regression Coefficients of the Negative Binomial Regression Model Applied to Illinois Data from 3,973 Segments (1,817 Miles) Aggregated for 6 Years (2001-2006)

Variable	Total Crashes	Fatal Injury	PDO	Day	Night	Daytime Fatal Injury	Nighttime Fatal Injury
Intercept	**–5.0743**	**–5.9166**	**–5.5362**	**–7.0307**	**–4.8645**	**–7.0871**	**–6.1145**
Edge line width	–0.0403	**–0.3295**	0.0326	**–0.1995**	0.0164	**–0.3986**	**–0.2021**
Lane width	**–0.0771**	**–0.0966**	**–0.0733**	**–0.1090**	**–0.0580**	**–0.1120**	–0.0720

Shoulder width	**–0.0121**	**–0.0339**	–0.0073	**–0.0320**	–0.0014	**–0.0391**	**–0.0316**
Log AADT	**0.8489**	**0.9607**	**0.8269**	**1.1263**	**0.6651**	**1.1064**	**0.7453**
Curve presence	**0.3146**	**0.6294**	**0.2038**	**0.3156**	**0.3375**	**0.3910**	**0.9120**
Dispersion	0.4238	0.5681	0.4446	0.5793	0.4133	0.8003	0.3184
Pearson chi-square/DF	1.2993	1.2655	1.2287	1.4470	1.1219	1.3075	1.0695
Variable	Wet	Wet Night	Single Vehicle	Single Vehicle Wet	Older Driver	Opposite Direction	Fixed Object
Intercept	**–7.7794**	**–7.5721**	**–3.5669**	**–5.7371**	**–7.0303**	**–14.7968**	**–4.6039**
Edge line width	**–0.2539**	–0.1727	–0.0044	**–0.2196**	–0.1127	0.2422	**–0.2865**
Lane width	–0.0608	–0.0270	**–0.0511**	–0.0146	**–0.0657**	–0.1174	–0.0528
Shoulder width	–0.0192	0.0015	–0.0072	–0.0149	–0.0167	–0.0202	**–0.0655**
Log AADT	**0.9893**	**0.7668**	**0.5547**	**0.6005**	**0.9307**	**1.5208**	**0.6926**
Curve presence	**0.4410**	**0.5484**	**0.4165**	**0.5715**	**0.1958**	**0.6133**	**0.7616**
Dispersion	0.7240	0.6887	0.4068	0.7235	0.5613	0.4919	0.5084
Pearson chi-square/DF	1.1055	1.0854	1.1337	1.0966	1.2856	1.2123	1.2565

Note: Significant (at α =0.05) effects are shown in bold.

For Illinois, raised reflective pavement markings (RRPMs) are used statewide, and rumble strips are used on interstates statewide. It needs to be noted, however, that the information on additional delineation and guidance measures (other than RRPMs and rumble strips) and on the roadway curvature was not available and could not be incorporated into the analysis. Therefore, the above observations are based on the assumption that the effects of the variables not in the database, such as those additional delineation/guidance measures and the roadway curvature, are the same (or averaged out) for the segments with and without wider edge lines.

In Michigan, before-after evaluations were conducted with 3 years (2001~2003) of before and 2 years (2005~2006) of after data obtained from 386 rural two-lane segments corresponding to 1,223 miles of rural two-lane roadways. Although regression-to-the-mean bias is not expected to be present (because wider lines were installed statewide in 2004), the empirical Bayes before-after evaluations (see, e.g., Hauer [*18*]) were employed to account for the remaining sources of bias such as differences between before and after study periods in traffic volumes, weather, vehicle fleet, driver characteristics, economic conditions, reporting practice, etc.

The empirical Bayes before-after evaluations (using the Illinois segments with 4-inch edge lines as the reference sites) resulted in the following crash reduction estimates: total (5.8 percent), fatal and injury (24.6 percent), PDO (3.9 percent), daytime (10.9 percent), nighttime (3.6 percent), daytime fatal and injury (28.7 percent), nighttime fatal and injury (39.5 percent), wet (30.9 percent), wet night (33.2 percent), single vehicle (1 percent), single vehicle wet (27.6 percent), single vehicle night (0.9 percent), and opposite direction (39.3 percent). All of these crash reduction estimates but nighttime, single-vehicle, and single-vehicle night crashes, were statistically significant at the 95 percent level. The researchers are finalizing their rural two-lane analyses with the addition of data from the Kansas Department of Transportation.

SUBJECTIVE EVALUATIONS

Opinions of the driving public have been used by transportation agencies to evaluate or score the agency's performance and, in some cases, are used to assist in policy decisions. Subjective evaluations can serve as an indicator of customer desire, but the results are not always tied to improvements in safety or what the drivers actually need to drive safely.

A public opinion survey published by the South Dakota Department of Transportation in 1997 shows that “keeping stripes visible” was the third-highest ranked attribute out of 21 for resource allocation (money and services) as rated by both 768 members of the driving public and 32 state legislators (*19*). A follow-up public opinion survey in 1999 showed that 81 percent of the 734 respondents felt that poor pavement markings would “somewhat interfere” or “very likely interfere” with safe travel (*20*).

The American Association of Retired Persons (AARP) had 18 of their instructors drive a test course in both daylight and darkness. The drivers were interviewed, and 94 percent of the respondents said that 8-inch edge lines affect the way they drive, especially as an aid to staying on the road and in their lane (*21*). Research by Ohme (*22*) reported that drivers participating in a field detection distance evaluation generally judged wider markings as more favorable than 4-inch markings. Similar results were observed by Pietrucha et al. (*23*) in simulator evaluations of 8-inch versus 4-inch edge lines. However, the researchers in both cases found that perceived quality and brightness of markings did not correlate well with objective end-detection performance for markings of different widths.

There have been a number of publications that document what can be considered minimum retroreflectivity levels as judged by nighttime drivers operating vehicles in a range of conditions. These studies are subjective in nature, but their results provide a reasonable sense of what drivers think they need to drive safely at night. Note, however, that the participants in these research efforts, or any typical nighttime driver, might not know what they really need from a pavement marking to drive safely. Despite this caveat, the recommendations for minimum retroreflectivity levels, based on driver preference (shown in TABLE 2) are generally consistent with results ranging from 80 to 130 mcd/m^2/lx. (*24, 25, 26, 27, 28*).

TABLE 2 Minimum and Desired Retroreflectivity Levels

Year of Research (Reference)	General Minimum Recommendation (mcd/m²/lx)	General Desired Recommendation (mcd/m²/lx)
1986 (*24*)	100	300-400
1991 (*25*)	93	Not applicable
1996 (*26*)	121	Not applicable
1998 (*27*)	80-120	200
2002 (*28*)	130	Not applicable

While several studies have evaluated the public perception of pavement marking brightness, there have been no documented efforts describing how well department of transportation (DOT) visual assessments correlate to measured retroreflectivity or how well DOT personnel are able to subjectively estimate retroreflectivity. A nearly completed Texas Department of Transportation (TxDOT)-sponsored study is currently evaluating the accuracy of DOT personnel's visual assessment of pavement marking retroreflectivity under a variety of typical nighttime roadway conditions (*29*).

A driving course was selected that had markings of varying retroreflectivity levels (80 to 700 mcd/m^2/lx) and the following roadway characteristics:

- pavement type (new asphalt, aged asphalt, concrete, or seal coat);
- lighting conditions (no fixed lighting or fixed lighting); and
- speed (≤40 mph, 45 to 55 mph, or ≥60 mph).

State DOT personnel drove the course and were asked to visually assess the retroreflectivity. Days before the visual assessment, the researchers thoroughly measured marking retroreflectivity. The researchers are comparing the visual assessment against the measured retroreflectivity levels to determine if visual nighttime inspection is a viable method to evaluate pavement marking retroreflectivity. The researchers are also assessing if the varying conditions have any influence on the ability to consistently rate different sections.

EFFECT OF PAVEMENT MARKINGS ON VEHICLE OPERATIONS

Measures such as speed and lateral position in the travel lane are surrogate measures for safety that are commonly used in the absence of crash data. The following subsections describe recent research that relates to the effect of pavement markings on lateral position and speed.

Vehicle Speed

While there have been a number of studies that used vehicle speed as a measure of pavement marking performance, most show no significant effect in absolute speed difference or, perhaps more importantly, speed variance (which is strongly correlated with crash rates [*30, 31*]) . For instance, in 2004 van Driel et al. (*32*) performed a meta-analysis of vehicle operating speeds based on edge line presence. The range of reported before-after results was –3 mph (reduction in mean speed) to +8.1 mph. An overall increase in mean speed after installing edge lines on roadways that previously only had a centerline was less than 0.5 mph. The authors came to the conclusion that the net speed effect was essentially zero.

In 2005, researchers from Louisiana reported on a before-after study of adding edge lines to narrow two-lane highways (with pavement widths of 20 to 22 feet) (*33*). Conclusively, the researchers found that the addition of an edge line on narrow two-lane highways did not impact vehicle speeds, day or night.

A recent study performed by Donnell et al. (*34*) for FHWA focused on the effectiveness of pavement marking delineation on curves to induce consistency in vehicle speed and lateral position based on a nighttime driving experiment. Based on the results of the present nighttime driving experiment, the use of brighter or wider pavement markings does not improve speed consistency between an approach tangent and the midpoint of a horizontal curve.

Tsyganov et al. (*35*) conducted a before-after study on rural two-lane highways where edge line markings were added. The highways had lane widths of 9, 10, and 11 feet. The researchers discovered that there were no significant differences in vehicle speeds before and after adding edge lines to the narrow highways. They also learned that there were no statistical differences in vehicle speeds when considering daytime versus nighttime conditions. The researchers' findings consistently showed that speeds slightly increased in all conditions after edge lines were applied, but the differences were not deemed statistically significant. They also showed that their absolute speed standard deviations were all less than 1 mph.

Many experts believe that drivers reduce speeds based solely upon their perceived risk. For instance, if drivers perceive sharp curves, narrow lanes or shoulders, steep roadside drop-offs, low side friction, etc., they will lower their speeds accordingly.

Lateral Vehicle Position

While research shows that the variance of vehicle lateral placement is strongly correlated with crash rates, there have been inconsistent findings related to the effect of pavement markings (*36*, *37*). A meta-analysis of lateral vehicle position was performed by van Driel et al. (*32*). Based on research conducted in the United States, the change in mean lateral position after installing edge lines on roadways that previously only had a centerline was approximately 0.5 inches toward the centerline. The range of reported before-after results was a –10.5-inch shift (toward the centerline) to a +14-inch shift away from the centerline. The authors came to the conclusion that the net lane position effect was essentially zero.

The work previously described by Donnell et al. (*34*) resulted in findings that indicate there is little evidence to show that enhanced pavement markings change the way in which motorists transition from a tangent into a curve. As such, the authors concluded that use of enhanced pavement markings does not improve driver lane position differential between an approach tangent and the midpoint of a horizontal curve.

On the other hand, Cottrell (*38*) compared the lateral vehicle position of vehicles using 4- and 8-inch-wide edge lines. The results indicated that lateral vehicle position variance was unchanged at locations with a 4-inch edge line but was lowered during both day and night for the 8-inch edge line condition.

The research conducted in Louisiana also investigated lateral placement as a function of adding edge lines to rural two-lane highways (*33*). Their before-after measurements show that edge lines help drivers confine their traveling path, particularly at night. They found that with edge lines, centralization of vehicles' position is more apparent at nighttime and drivers generally position their vehicle away from the edge line, irrespective of the roadway alignment.

Tsyganov et al. (*35*) also evaluated lateral placement after adding edge lines to narrow two-lane highways. They discovered a reduction in vehicle lateral placement variability, meaning vehicles were more consistently following a specific path. The exact location of that path depended on the overall lane width. For the 9-foot lane width, the vehicle path shifted closer to the newly installed edge line, especially in the curve sections. For 10-foot lane widths, there were no consistent changes noted. However, for the 11-foot lane width highways, the majority of the drivers moved closer to the centerline, especially on the curve sections. However, all the changes were subtle.

MEASURES OF PAVEMENT MARKING VISIBILITY

In this paper, visibility evaluations include research directed toward the identification of correlation rates between pavement marking visibility (measured in terms of retroreflectivity) and crashes, and research evaluating the detection of pavement markings with various characteristics and properties. Detection distances are thought to be a surrogate for crash data in that longer detection distances have a positive effect on vehicle-control measures and, consequently, crashes. Because of this, incremental visibility improvements provided by pavement markings have been viewed as a proxy for improved roadway safety, although no direct link has been established.

Studies of Visibility in Terms of Retroreflectivity and Crashes

Recently, there have been several attempts to statistically link pavement marking retroreflectivity levels to crash rates. A significant challenge has been that pavement marking retroreflectivity levels are dynamic in that they continuously change. Attempts to model pavement marking retroreflectivity degradation curves have not been widely successful (*39, 40*). While there is some predictability to pavement marking retroreflectivity (it is generally accepted that ADT is a significant predictor variable), it can change unpredictably and substantially as a function of frequency and intensity of rain (to clean markings), quality of installation, or even the condition of the pavement. Therefore, it is difficult to know the retroreflectivity levels of the pavement markings at the exact time and location of each crash. While crash data are available, researchers have had to make assumptions regarding the retroreflectivity levels for their analyses. Some researchers model retroreflectivity using various sources of measured data, while others make assumptions about the retroreflectivity without measurements. This section of the paper describes attempts to statistically link pavement marking retroreflectivity levels to crash rates.

In 2006, researchers in New Zealand studied the safety impacts of brighter pavement markings and concluded that there was a not a conclusive improvement in safety (*41*). In 1997, New Zealand implemented a minimum maintained retroreflectivity policy of 70 mcd/m^2/lx for their state system. Using a before-after approach, the authors compared the crash rates before the change in policy. They assumed that markings were brighter during the after period. It should also be pointed out that, in New Zealand, all state roadways are delineated as a function of traffic volume. As volumes increase, they progressively apply the following treatments: delineators, centerlines, edge lines, and then RRPMs. Therefore, roadways with centerlines had delineators too. Previous research in the United States has shown that supplemental delineation treatments, such as delineators or RRPMs, overpower the potential effect of pavement markings (*42*).

Also in 2006, the results of a National Cooperative Highway Research Program (NCHRP) study were published with the following conclusions: "…the difference in safety between new markings and old markings during non-daylight conditions on non-intersection locations is approximately zero" (*43*). While the study incorporated large amounts of crash data and utilized the latest statistical techniques, there were significant limitations to the study. For instance, the research only included crashes from California and *modeled* retroreflectivity (no measurements were made). While the study included efforts to overcome the possible limitations in modeling retroreflectivity, these efforts presuppose that markings in California never reach a value where there is an adverse impact on safety. The pavement marking maintenance policy of California is such that they restripe their higher-volume highways up to three times a year with paint, or every two years with thermoplastic markings. As a result, there is only the occasional roadway with retroreflectivity levels below 100 mcd/m^2/lx.

Overlooking the concerns regarding the modeled retroreflectivity levels, perhaps even more concerning is the binning of the modeled retroreflectivity levels. The binning thresholds were derived linearly, which by itself is a limitation since the performance of retroreflectivity has been repeatedly shown to be best modeled logarithmically rather than linearly (*47, 48*). In addition, the authors binned the modeled retroreflectivity data such that the lowest bins for the edge lines included retroreflectivity levels from 21 to 183 mcd/m^2/lx, thus including both inadequate levels and near-desired levels in the same bin (see TABLE 2). Eight additional bins included retroreflectivity levels up to 413 mcd/m^2/lx. Therefore, all binning used in the analyses included levels deemed to be acceptable or at least above minimum retroreflectivity levels. Combined, these limitations and concerns seriously challenge the quoted concluding remarks shown above.

In 2007, researchers reported results from an effort to develop a statistical association between measured pavement marking retroreflectivity and traffic crash frequency (*44*). The results suggest that increased levels of the average pavement marking retroreflectivity on multi-lane highways may be associated with lower expected target crash frequencies; however, the association is small in magnitude and not statistically significant. On two-lane highways, the association between pavement marking retroreflectivity and crash frequency is larger in magnitude and marginally significant. While this study used measured retroreflectivity levels (recorded once per year), it should be noted that all the retroreflectivity data were well above what might be considered minimum levels, and even near what might be considered desired levels (all data were above 100 mcd/m^2/lx with an overall average of 240 mcd/m^2/lx). These researchers are continuing to evaluate their data using innovative techniques such as modeling retroreflectivity using neural networking techniques.

In 2008, a similar effort was reported that included 3 years of measured retroreflectivity (measured once per period) in Iowa (*45*). These data were analyzed along with crash records from the same year. The distributions and models of the entire database, and a subset including only two-lane highways, did not show that pavement marking retroreflectivity correlated to crash probability. When truncating the data to only records with retroreflectivity values ≤ 200 mcd/m^2/lx, a statistically significant relationship was determined. However, the correlation was small. This research is also being continued using retroreflectivity thresholds near the generally accepted minimum levels of 100 mcd/m^2/lx.

Studies of Visibility in Terms of Detection Distances

Pavement marking detection distances are usually measured with two different techniques. In a static setup, the driver counts the number of skip lines visible. In a dynamic setup, where the research participant is driving the vehicle, the driver is tasked with detecting either the beginning or end of a long line, an isolated skip line (*52*), or a discontinuity such as a taper (*46*). The results are reported in maximum nighttime detection distances. These studies are usually conducted with pavement markings of various retroreflectivity levels (measured dry or wet), of different widths, and from different vehicles (in consideration of their size and headlamp type). The studies have repeatedly shown that pavement marking detection distances are correlated to retroreflectivity in a logarithmic fashion (*47, 48*).

While the use of wider pavement markings continues to grow across the United States (*49*) and research results are looking favorable in terms of the impact on safety, the results of studies based on maximum detection distances of pavement marking widths are inconclusive. On one hand, a number of research efforts show increased visibility for wider lines (*22, 50, 51*), while on the other hand, research findings also show that there are no consistent statistical or practical differences (*23, 52*). An empirical study has shown that theoretical calculations of marking detection distance as a function of marking width are invalid, and more work is needed to develop mathematical relationships between marking width and detection distances (*53*).

OTHER PAVEMENT MARKING STUDIES

While this paper includes some of the most common and often cited measures of pavement marking performance, it is not intended to be 100 percent comprehensive. Other techniques have been used successfully to evaluate pavement markings and measure their benefits. One approach is based on psycho-physiology measures that account for the workload of the driver. Another approach monitors drivers' eye movements to identify how drivers use pavement markings during their driving tasks. Examples of each of these techniques are described below.

Driver Workload Measures

Tsyganov et al. (*35*) conducted a unique study on rural two-lane highways where edge line markings were added. The highways had lane widths of 9, 10, and 11 feet. The researchers tested driver workload before and after edge lines were installed. For workload, the researchers monitored heart rate. They found that the addition of edge lines on narrow two-lane highways decreased workload at nighttime conditions for both free driving conditions (i.e., no oncoming vehicles) and meetings with oncoming traffic. For instance, the addition of edge lines showed an average 15 percent decrease in the total time when participants were deemed to be experiencing high mental workload rates during nighttime driving conditions. On average, the mean nighttime mental workload rate was reduced by 12 percent after adding edge lines. Other means of measuring driver workload have been used in the past as well, including galvanic skin response, steering fluctuations, accelerator and brake pedal activations, etc.

Driver Eye-Tracking Measures

As described above, visibility-related research provides inconclusive results in terms of increased detection distances provided by wider markings. However, an ongoing safety study is demonstrating that wider markings can reduce crashes on rural two-lane highways.

Pavement markings provide two primary functions: previewing the roadway alignment (using far or foveal vision) and maintaining lane position (using near or peripheral vision). Foveal detection tasks have been thoroughly studied to no avail (i.e., inconsistent findings) in terms of identifying benefits of pavement marking width. Therefore, it seems reasonable to postulate that peripheral visibility measures may provide a stronger visibility measure of effectiveness in terms of identifying benefits of wider pavement markings. In fact, McKnight (*54*) conducted research showing that intermediate crash measures, such as lane positioning attention management (where drivers focus their attention), are related to peripheral vision. The researchers showed that major improvements in lane keeping are associated with wider pavement markings (studied under low contrast levels).

TxDOT is sponsoring research aimed at determining how wider pavement markings may assist the driver in lane keeping tasks by allowing the foveal focus (i.e., driver attention) to be available more often for other driving tasks because of the enhanced information available through peripheral vision. A hypothesis to be tested is that the peripheral vision system, at least when constrained to a particular boundary and known scene, such as the view through the windshield during nighttime driving, is capable of target recognition using very low cognitive power.

The premise is that a driver's central vision, which is only directed to short-distance pavement marking viewing when needed (i.e., low-visibility conditions or unexpected targets), would be more available for other driving tasks such as scanning the roadside, reading signs, checking mirrors, etc. Undoubtedly, there are endless targets recognized in the periphery that somehow are processed as insignificant and therefore cause no need for our central vision focus. If wider markings can reduce the amount of time the central focus is needed on short-range pavement markings, then the potential benefits of wider markings could be realized. Drivers could then manage their foveal vision on other driving tasks as noted above, therefore ultimately providing a safer driving environment.

The research requires drivers to navigate a serpentine test track in an instrumented vehicle during nighttime conditions while wearing state-of-the-art eye-tracking equipment. In stage one, the drivers' view is controlled so that they see the course under two conditions. The first condition is with their standard low-beam headlamps. The second condition is similar except that the near-field illumination is removed (i.e., occluded). Comparison of lateral placement, speed selection, and eye-tracking data will allow the researchers to test the strength of the premise regarding how drivers rely on pavement markings using peripheral vision.

Assuming this premise holds true and is validated through the testing described above, the researchers will repeat the experimental plan in three phases (stage two). The differences between each phase will be the pavement marking retroreflectivity and the pavement marking width. Using this approach, it is envisioned that the research could develop relationships demonstrating how the use of wider lines permits drivers to manage their vision system in a more effective manner, which would lead to a reduction in crashes. This research has the potential for a significant breakthrough in terms of quantifying the benefits of wider markings, particularly demonstrating how drivers use pavement markings at night to maintain their lane position.

FINDINGS

Despite a national standard on the uniform application of centerlines, lane lines, and edge lines—which is designed to promote highway safety and efficiency—every 21 minutes a highway death occurs from a lane departure. While there is a national effort to keep drivers on the road, and pavement marking is one potential countermeasure (with an estimated annual expenditure in the United States of $2 billion), there is a need for a consolidated effort to bring together recent and ongoing research findings demonstrating a renewed perspective on the benefits of pavement markings.

Crashes

Almost all the recent crash research has been geared toward adding edge lines to highways. Recent crash studies as well as those more than a half century old have conclusively shown that adding edge lines to rural two-lane highways can reduce crashes and fatalities. Some of the findings demonstrate that these benefits can be achieved with narrow pavement widths (18 feet or less) and low ADTs (as low as 1,000 vpd). The benefits have been shown to be statistically significant in areas of all terrain types, and in all locations during nighttime conditions and nighttime low-visibility conditions.

In terms of vehicle speeds and lateral placements, there appears to be either no real impacts or, at most, only subtle impacts as a result of adding edge line markings. This includes narrow two-lane highways and day and night conditions.

In a recent study, driver workload was reduced after edge lines were added to narrow two-lane highways.

Wide Markings

Earlier crash studies conducted on wider pavement markings were inconclusive, showing no particular benefit. However, current research using the latest statistical analysis techniques is showing the potential benefit of wider pavement markings on rural two-lane highways. For instance, edge line width has been found to statistically lower nighttime fatal and injury crashes in an ongoing analysis of two state's data, which is particularly useful since the nighttime crash rates is approximately three times higher than the daytime crash rate.

These new safety findings, though, are not supported by the latest visibility research, which has shown inconsistent findings related to increased detection distances from wider markings. The expectations are high for ongoing research to demonstrate how wider markings can lower crash rates. Using state-of-the-art eye-tracking equipment in an instrumented vehicle, researchers are currently evaluating how drivers use markings through both the foveal and peripheral vision system.

Retroreflectivity

While the FHWA works to develop minimum maintained retroreflectivity levels for pavement markings (*55*), several agencies have conducted subjective evaluations of their roads and pavement markings to identify what drivers think they need. Having highly visible pavement markings is a high-ranking desire among the public. It also appears that the public prefers to have their markings maintained to at least 80 to 130 mcd/m^2/lx.

Research is currently underway to assess whether DOT personnel can adequately judge marking retroreflectivity during nighttime visual inspections. This will be a key element of managing retroreflectivity in terms of maintaining adequate levels of retroreflectivity for safe nighttime driving.

The correlation between retroreflectivity and crashes has been a topic of recent research. Several efforts have been completed to identify a statistical correlation, but no conclusive evidence has yet to be generated. Each effort has been unique and innovative in terms of the study approach, but they either used assumed or modeled retroreflectivity data, or retroreflectivity data that were measured but much higher than what has been judged to be a preferred minimum, 80 to 130 mcd/m^2/lx. Continued research using measured retroreflectivity data and advanced analysis techniques is generating promise in terms of identifying the elusive correlation between retroreflectivity and crashes.

DISCUSSION

It is evident from this paper that the arena of pavement marking research is active and delivering findings demonstrating the effects of pavement markings and their characteristics. Despite the new and exciting findings, it also appears obvious that more work is needed and opportunities exist to develop safety-based policies and performance-based specifications.

For instance, there is an excellent opportunity to investigate how the MUTCD pavement marking warrants could be modified based on safety-supported criteria. Speed is not currently considered in the criteria. What if the policy on pavement marking applications was tied to minimum retroreflectivity levels in a way that provides a synchronized approach so that higher-speed roadways have higher requirements of retroreflectivity (to provide drivers with adequate preview times from low-speed to high-speed roadways)?

Another area of needed research is thorough analyses of crashes by key factors such as pavement marking presence, lane widths, ADT, functional classification, curve presence, and volume. This should include state and local roadways. The results of thorough analyses could be used to support changes to the MUTCD policies that would provide safety-supported policies for when to apply pavement markings.

Continued work is needed to develop a correlation between retroreflectivity and safety. Although existing work is ongoing, the task is challenging. A key component of having a successful effort is having rich data sources. In this case, there needs to be a rich data source for both crashes and measured pavement marking retroreflectivity. The most challenging item is having retroreflectivity data that are reliable and represent the condition of the pavement marking during crash periods.

Another area of research that is potentially rich with information is further study of how drivers use pavement markings during daytime and nighttime conditions. More information is needed to better understand how driving behavior shifts during low-visibility conditions, when negotiating horizontal curves, or when oncoming traffic approaches at night.

There are many advances underway. Pavement marking technologies are producing more durable markings, brighter markings, and markings that continue to retroreflect even during rainy conditions. Agencies are continuing to use pavement markings on rumble strips for added visibility and durability. Many agencies are developing successful pavement marking management tools that include innovative performance measures. The specifications for pavement markings are also evolving to accommodate new technologies and innovative pavement marking management practices. These efforts, and others, have been shown to be effective. As noted earlier, the Missouri Department of Transportation has seen a 25 percent reduction in lane departure crashes since implementing policies to help keep drivers on the road.

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