# Towards Improved Management of Pavement Markings and Markers

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## Abstract

This paper outlines key points of the extensive literature review and state of the practice by iTRANS Consulting Inc. conducted for the Transportation Research Board National Cooperative Highway Research Program 17-28 whose objective is to develop guidelines for use of pavement marking materials and markers based on their safety impact and cost-effectiveness.

The Federal Highway Administration is actively pursuing research to determine the minimum retroreflectivity requirements for pavement markings. In all cases, the research to determine minimum retroreflectivity requirements is based on drivers' minimum detection distances. As is no surprise, research to determine minimum detection distances has determined that brighter markings can be seen further away; there is an unwritten assumption is that increasing minimum detection distances increases safety. Unfortunately, there are situations, such as sharp curves with low design standards, where in fact *increasing the detection distance increases the number of crashes*. With increased visibility of pavement markings and markers, possibilities exists that drivers can feel overconfident and drive too fast for the road conditions causing crashes. This leads to the question; "what are the *maximum* retroreflectivity requirements for different road classes?"

The condition and effectiveness of pavement markings degrade over time due to a variety of factors, as identified by previous research. When installing pavement marking materials, the challenge for transportation agencies is to reconcile the different service longevity and costs of the various pavement marking materials with the remaining service longevity of the existing pavement surface, while maintaining an acceptable level of performance for road users.

## Introduction

The Federal Highway Administration (FHWA) is actively pursuing research to determine the minimum retroreflectivity requirements for pavement markings. In all cases, the research to determine minimum retroreflectivity requirements is based on drivers' minimum detection distances. As is no surprise, research to determine minimum detection distances has determined that brighter markings can be seen further away. The unwritten assumption is that *increasing minimum detection distances increases safety*. Unfortunately, we know this assumption is not always true. NCHRP Report 518 (4) on Permanent Raised Pavement Markers determined that installing markers on sharp curves with low daily traffic volumes and low design standards actually increases the number of crashes by as much as 43%. This is a situation where *increasing the detection distance increases the number of crashes*.

What is the probability that there are conditions where increased visibility of pavement markings and markers is causing drivers to feel overconfident and drive too fast for the road conditions ahead causing crashes? Is there any possibility that setting too-high marking and marker minimum retroreflectivity requirements will in fact make all drivers less safe? What are the *maximum* retroreflectivity requirements for different road classes? Pavement markings and markers cover roadways across the nation, and as road safety professionals we need to know the answers to these very relevant questions.

This paper outlines key points from the literature review conducted for NCHRP Project 17-28, Pavement Marking Materials and Markers: Safety Impact and Cost-Effectiveness, whose objective is to develop guidelines for use of pavement marking materials and markers based on their safety impact and cost-effectiveness. This paper is the result of a review of research conducted by various state DOTs, academic institutions, private- and public-sector materials testing laboratories, manufacturers and suppliers of materials, and the National Transportation Product Evaluation Program (NTPEP), derived from the following sources:

- Personal and organization libraries of research team members;
- Institute of Transportation Engineers (ITE) digital library;
- TAC (Transportation Association of Canada) library catalogue;
- TRIS (U.S. National Transportation Library);
- IRRD (International Road Research Database);
- OECD Library (Organization of Economic Cooperation and Development); and
- FHWA publications.

Relevant publications were located by conducting manual and online searches. The online search was initiated with an Internet search of well-defined keywords. In total, the research team reviewed more than 200 publications. A few reports, not cited in these databases, were accessed through personal contacts. The References section lists only cited publications. The complete literature reviewed covered topics related to pavement markings and markers such as:

- Visibility and retroreflectivity;
- Safety;
- Human factors;
- Implementation guidelines;
- Specifications and maintenance practices; and
- Cost benefits.

The four main purposes for using road markings and symbols, as identified by Elvik and Vaa (10), are to:

1. Direct traffic by indicating the path of the traffic on a road in relation to the surroundings;
2. Control traffic, for example, by reserving certain parts of the road for certain traffic groups (e.g., public transport), and by allowing or prohibiting overtaking and lane changing;
3. Warn road users about specific or hazardous conditions related to the road alignment; and
4. Supplement and reinforce information traffic signs.

Some of the more common pavement marking materials in use today include waterborne paints, thermoplastic, durable tape, and epoxy.

### Waterborne Paints

Waterborne traffic paints are the most widely used and least expensive pavement marking material available. Glass beads are either pre-mixed into the paint or dropped onto the waterborne paint while the marking is still wet to provide retroreflectivity. Paints generally provide equal performance on asphalt and concrete pavements, but have the shortest service longivity of all pavement marking materials. Waterborne paints are single-component paints that are ready for application and do not require additional ingredients (26). The relatively low cost is the major advantage of waterborne paints (3).

Compared to other pavement marking materials, waterborne paints wear off rapidly and lose retroreflectivity quickly after exposure to environmental factors such as high traffic volumes and winter-maintenance activities. Although waterborne paints are still the most widely used pavement marking material, none of the 19 state agencies surveyed by Gates et al. (13) recommended them as the top-performing long-term pavement marking material. Several state agencies even stated that they use paint as an interim marking material until they can apply a more durable material. McGinnis (23) further added that given the short service life of waterborne paint markings, many state agencies often choose to repaint those markings on a fixed schedule instead of restriping when some objective measure such as retroreflectivity drops below a specified threshold. With the easy market availability of more durable pavement marking materials, Gates et al. (13) suggested that paint is not a suitable marking material for high-volume roadways despite its inexpensive application cost.

### Thermoplastic

Thermoplastics materials have been used since the 1950s and consist of four basic components: binder, pigment, glass beads, and filler (sand or calcium carbonate). Due to its moderate cost and durability, thermoplastics are one of the most widely used pavement marking materials. In fact, the vast majority of longitudinal pavement markings in some states, such as Texas, are thermoplastic. One of the added advantages of using thermoplastic is that the material can be re-applied over older thermoplastic markings, thereby refurbishing the older marking as well as saving on the costs of removing old pavement markings. Although thermoplastic materials usually perform very well on all types of asphalt surfaces, there have been mixed results when they have been applied on concrete pavements (13,2). One of the disadvantages of thermoplastic is its color and appearance. Thermoplastic is grayish, making it less visible by day, and has a tendency to crack. Furthermore, the application of thermoplastic marking materials in areas with colder climates is limited due to the poor adhesion of the material to pavement surfaces in lower temperatures. Successful thermoplastic performance on concrete is highly dependent on correct thermoplastic material formulation, proper surface cleaning, moisture removal, and priming (if necessary) before installation.

### Durable Tape

Several types of durable tapes are currently in use, including flat preformed tape and profiled preformed tape. Tapes tend to have a high initial cost and are generally used in areas that require minimal marking and need to perform well in areas subject to severe weather conditions. Glass beads that provide retroreflectivity in tapes are incorporated into the tape material during industrial manufacturing. Freshly installed tape markings typically have initial retroreflectivity values 4 to 6 times that of waterborne traffic paints. The consensus is that if applied properly, tape will provide between 4 and 8 years of use. The successful performance on tape depends on many stringent requirements, including proper pavement and air temperature, adequate preparation of the road surface (e.g., dry and free of existing markings), the use of quality adhesives (if markings are overlaid), and the need for proper curing time. Nevertheless, according to many agencies, the advantages of using preformed tape appear to outweigh the disadvantages or strict requirements. In fact, permanent preformed tape was most frequently recommended as the marking material with the best long-term performance by 19 state DOTs surveyed (13). In general, inlaid markings (where the tape is pressed into the pavement surface while it is still warm) outlast overlaid markings (where tape is adhered to the pavement surface through the use of an adhesive or installed by heat fusion) and both are snowplowable.

### Epoxy

Epoxy is a type of two-component material that is produced on site through the reaction of two separate chemical reactants. Epoxy paint has traditionally been viewed as a marking material that provides exceptional adhesion to both asphalt and concrete pavements when the pavement surface is properly cleaned before application (13). The strong bond that forms between epoxy paints and both asphalt and concrete pavement surfaces results in the material being highly durable when applied on both pavement surfaces. Glass beads are either applied on the surface of the stripe while it is still wet or is pre-mixed into the first component. Gates et al. (13) pointed out that another usual complaint with many epoxy materials is the long drying times (sometimes more than 40 minutes) that limit the use of this material under high traffic conditions. Regardless of its shortcomings, a survey conducted by Gates et al. (13) found that more agencies used epoxy markings on concrete surfaces with high traffic volumes than any other pavement marking material, although the majority of the agencies responding to the survey selected preformed tape as the top performer on concrete

Pavement markings and markers are unlike many other engineering safety treatments in that the treatment is continuously changing over time. Most treatments remain unchanged over time, such as for example installing a dedicated left turn lane to deal with rear-end crashes. The net safety effect of installing the left turn lane is expected to remain constant over time given no change in the traffic volumes, drivers, or road environment at the left-turn lane location. Unlike many other engineering treatments which for the most part can be assumed not to have changed in the short-term, pavement markings and markers change in a measurable/quantifiable way on a monthly basis from the date of installation. The nighttime retroreflectivity and daytime visibility of pavement markings and markers degrades over time as the markings and markers separate from and are worn off the pavement. This change in the condition of the markings and markers is critical in terms of the pavement marking's safety performance.

The daytime visibility of pavement markings and markers can be very different than their nighttime visibility. The nighttime visibility of pavement markings and markers is usually discussed in terms of *retroreflectivity*.

### Retroreflectivity

The condition and effectiveness of pavement markings degrade over time due to a variety of factors, as identified by Thamizharasan et al.(37). These factors include traffic volumes, the presence of heavy vehicles, weather/climate, quality control in the application of the marking material, age, and the type of pavement surface. When installing pavement marking materials, the challenge for transportation agencies is to reconcile the different service lives and costs of the various pavement marking materials with the remaining service life of the existing pavement surface, while maintaining an acceptable level of performance for road users. Given that longitudinal pavement markings provide visual guidance to drivers, the key issue is to understand what constitutes an effective visible pavement marking.

The visibility of pavement markings at night is dependent on their retroreflectivity, which represents the portion of light from a vehicle's headlight reflected back toward the eye of the driver of that same vehicle, as discussed by Migletz et al.(24). Retroreflection means that the light is reflected back at the same angle that it is projected. If light from the headlights was to be perfectly retro-reflected, it would not reach the driver's eyes, which are above the headlights. Since retro-reflection is imperfect, some of the light reaches the driver's eyes, increasing the contrast between the delineator and the low-reflectance pavement background. The higher the percentage of light that is retro-reflected, the greater the contrast and the further away the delineator will be seen. Both the retroreflectivity value (represented by the coefficient of retroreflected luminance, $R_L$, the coefficient of retroreflected luminance, in millicandelas per square meter per lux (mcd/$m^2$/lux).) and the degree of contrast between the retroreflectivity of the pavement marking and the retroreflectivity of the adjacent pavement surface are important to the visibility of a pavement marking (24).

The retroreflectivity of pavement markings is the most important factor when determining driver detection distances at night. The proposed FHWA guidelines for the minimum retroreflectivity of pavement markings, as reported by Migletz and Graham (26), is given in Table 1.

**Table 1. Minimum in-service retroreflectivity guidelines for pavement marking materials recommended by the FHWA (mcd/$m^2$/lux)**

| | | Speed Classification[a] | | |
|---|---|---|---|---|
| | | Non-Freeway | Non-Freeway | Freeway |
| | Option 1 | ≤40 mph | ≥45 mph | ≥55 mph |
| | Option 2 | ≤40 mph | ≥45 mph | ≥60 mph<br>>10,000 ADT |
| Material | Option 3 | ≤40 mph | 45–55 mph | ≥60 mph |
| White | | 85 | 100 | 150 |
| White with/RRPMs[b] | | 30 | 35 | 70 |
| Yellow | | 55 | 65 | 100 |
| Yellow with/RRPMs[b] | | 30 | 35 | 70 |

Note:

a - Retroreflectivity values are measured at 30-m (98.4-ft) geometry.

b - Levels of retroreflectivity for the material classifications "White with RRPMs" and "Yellow with RRPMs" are for roads with supplemental delineation aids, retroreflective raised pavement markers (RRPMs), and/or roadway lighting.

**Source: Adapted from Migletz and Graham (26)**

## Retroreflectivity Performance Requirements

Visibility is often measured in terms of the detection of a target at a distance. For example, in the case of retroreflective centerlines and edgelines on a two-lane rural road with shoulders, the preview distance at which the curve is visible under nighttime conditions would be a measure of the curve's visibility. In the United States, the 1993 Transportation Appropriations Act stated "The Secretary of Transportation shall revise the Manual of Uniform Traffic Control Devices to include - (a) a standard for a minimum level of retroreflectivity that must be maintained for pavement markings and signs, which shall apply to all roads open to public travel" (11). FHWA has been conducting research on visibility needs for drivers for some time. The underlying assumptions of specifying minimum retroreflectivity standards are two-fold:

1. Increased retroreflectivity equals increased visibility for drivers under nighttime conditions; and
2. Increased visibility equals increased safety for road users.

The first assumption is usually tested under controlled conditions in a simulator or in the field. Such controlled experiments conclude that with an increase in the amount of light reaching the driver's eyes, the visibility of those lighted features are visible at greater distances. The second assumption is much more difficult to prove because at first glance, the statement seems intuitively obvious given the inverse statement, "If I can't see then I can't be safe." If not seeing is unsafe, then seeing must be safe. But seeing what? Visibility under controlled conditions is measured in terms of a detection distance. However, the complexity involving a driving task cannot be boiled down to a single number given as a distance measurement. In other words, defining visibility simply as a detection distance misrepresents drivers' visibility requirements. Driving is a self-paced task that involves drivers adapting to what and how far they see. The adaptation may take the form of externally visible behavior (such as speed choice) or behavior that is not easily observable (e.g., arousal, alertness, fatigue, and drowsiness). There is no general theory that allows predicting whether the adaptation induced by some change (e.g., more visible edgelines) will reduce crash frequency or severity, or have the contrary effect. The assertion "more visibility leads to fewer crashes" may not necessarily be valid. Thus, what is required to answer the question is empirical support showing that an improvement in the index is causally associated with fewer or less severe crashes.

## Contrast

The visibility of markings and markers is dependent on the physical aspects of the delineation, their placement, head-lighting, highway geometry, and driver visual capabilities. Drivers detect the presence of markers and markings by means of *contrast*: differences in brightness between the delineator and the road surface. Contrast (the difference in brightness between two objects) can be defined using Equation 1 (calculation of contrast).

**Equation 1.**

$$C = \frac{L_T - L_B}{L_B}$$

where

$C$ = Contrast ratio,

$L_T$ = Target luminance (e.g. markings or markers), and

$L_B$ = Background luminance (e.g. pavement surface).

The use of Equation 1 for markings and markers should result in positive values from 0 to infinity. Using Equation 1 for targets with less luminance than the background will result in values ranging from 0 to –1.

**Human Factors**

Given the tendency for drivers to drive too fast at night under low-visibility conditions and "overdrive" low-beam headlights (40), Migletz et al. (25) defined the preview or visibility distance as the distance that the delineation provides the driver to see upcoming changes in the roadway. This distance must provide drivers with enough time to detect roadway features and changes in alignment ahead, and respond with steering and speed adjustments. The preview distance offered by pavement markings is particularly important when the view of the road ahead is limited and drivers are forced to depend on roadway and traffic information that is visible only from a short distance (26). In adverse weather conditions or during nighttime, this preview distance is dependent on the visibility of the pavement markings, which in turn is a function of the reflectivity of the markings and markers.

Many previous studies have attempted to determine driver requirements in terms of preview time for both short-range and long-range guidance (26). The consensus is that 2 seconds of preview time is required for short-range guidance in extreme situations during when a driver may be required to respond quickly to perceived hazards or changes in alignment. For long-range guidance, the general view is that a minimum of 3 seconds of preview time is required to allow for comfortable driving (26). Zwahlen and Schnell (40) investigated this concept further and recommended a preview time of 3.65 seconds (3.00 seconds of true preview time and 0.65 seconds of perception-reaction time) to accommodate drivers with a margin of safety and comfort. Consistent with the research conducted by Molino et al. (28), Zwahlen and Schnell (40) also showed that requirements for preview times could be substantially relaxed if markers were used along the centerline or lane line. In general, the concept of using a preview time implies a static view of the driving task rather than an adaptive one. Most driving simulator experiments, and even most field studies, assume a constant speed and use this constant speed as a base for preview time calculations. However, on the highway, drivers change their speed as a function of visibility and road conditions and do not maintain a constant speed.

Parker and Meja (32) found that driver age has a significant impact on the visibility (which was quantified using detection distances) of pavement markings at night. The field study found older drivers ($\geq 55$ years) tended to assign lower scores to pavement markings compared with younger drivers (<55 years). This observation is expected given that visual acuity is likely to diminish with age. However, it has also been shown that older drivers may sometimes assign higher subjective visibility ratings to pavement markings simply because they are aware of their visual limitations and have lower expectations in regards to the brightness or visibility of the pavement markings (20). Regardless, highway marking, signing, and other information road features for roads may not work adequately for drivers of all ages. In some cases, drivers 65 years old and over may need as much as four times more light to see as well as a 39-year-old driver (26).

In an attempt to structure the information deficiencies that can contribute to a crash, Taylor et al. (36) included the following driver information requirements, for curve navigation:

- Advance warning of curve;
- Location of beginning of curve;
- Direction of curve;
- Degree of curvature;
- Location of apex; and
- Lateral position limits.

The relationship between increasing detection distance, or visibility as discussed above, and speed is not well understood. One study by Zwahlen and Schnell (41) found that drivers do not decrease their driving speed as a function of reduced pavement marking visibility. Thus it may be that higher visibility conditions may cause drivers to drive at higher speeds, which may in turn increase the frequency and severity of crashes as they go too fast for conditions. Increasing retroreflectivity, thereby increasing detection distances, may not necessarily increase safety. The relationship between driver detection distances and driver behavior needs to be better understood to make definite conclusions about the effect of increased retroreflectivity requirements.

While there are several areas that are not as well understood as we would like, the top three research gaps regarding pavement markings and markers are as follows.

### Research Gaps

1. Relationship between safety and visibility for determining cost-effectiveness
2. Models of pavement marking and marker visibility
3. The human factors of marking and marker visibility

### Gap #1 - Relationship Between Safety and Visibility for Determining Cost-Effectiveness

A review of the literature has determined that the primary research gap concerning pavement markings and markers is a study of the relationship between *safety* and *visibility*. Safety is defined here as the number of crashes by severity (e.g. fatal, injury, property damage only). Visibility at night is defined here as the retroreflectivity of the delineation, and during the day is defined here as the percentage of marking surface area or number of markers remaining on the road surface, e.g. the durability of the marking.

The relationship between visibility and driver *performance* and driver *preference* has been studied (20,32,42,15,39). In addition, previous research has reviewed the overall safety effect of newly installed pavement markings (35,34,33,16,14,8) and markers (4,17,30,31,22).

However, underlying the study of the overall safety effect of a marking or marker is the assumption that the visibility of markings and markers is constant throughout the evaluation period. Unfortunately, the reality is that the visibility of markers and markings degrades over time. *The quantitative relationship between visibility and safety has yet to be determined*. In other words, how do different levels of visibility of markings and markers quantifiably affect the safety of highways? Understanding the relationship between visibility and safety is critical in:

- Establishing guidelines for the use of pavement marking material and markers

- Setting minimum retroreflectivity guidelines for pavement markings and markers

Previous research which has examined the relationship between visibility and safety has been inconclusive (18), or have failed to adequately address issues such as seasonality and the nonlinearity of traffic data(1). Currently, recommended minimum retroreflectivity guidelines are based upon driver performance and driver preference responses that were measured in the field or during simulator studies (11). Superior recommendations and guidelines for their use will be achieved when a cost analysis of pavement marking and markers are based upon safety effects. A proper cost analysis requires a *formalized structure* which takes into account total costs and total benefits for assessing the effectiveness of markings and markers. The literature reports (9) that agencies do not completely take into account service-life and all in-house costs when computing costs.

### Gap #2 - Models of Pavement Marking and Marker Visibility

The visibility of markings and markers change over time, in that markings and markers fade and wear off the road surface thus degrading their retroreflectivity and remaining percentage of surface area. The visibility of markings and markers can be measured in laboratories or through site visits, however, such direct measurements are costly. Alternatively, marking and marker visibility can be modeled (37). Accurate models to predict visibility over time are critical in terms of estimating the performance of markings and markers over time. Reliable predictions of performance can cost-effectively reduce the number of required site visits and marking inspections. There are numerous factors that have a significant influence on the rate of pavement marking degradation such as traffic volumes, heavy vehicle percentages, weather/climate, type of marking material, quality control in applying the marking material, type of pavement surface, roadway geometry, and snowplowing.

To summarize, a comprehensive engineering model which takes into account all of these factors does not exist. Improved models to predict marking visibility would be instrumental in quantifying the relationship between safety and visibility, and in practice in determining the most cost-effective selection and replacement cycles for pavement markings and markers.

### Gap #3 - The Human Factors of Marking and Marker Visibility

There are numerous questions related to the human factors of how driver behavior changes as a function of the visibility of pavement markings and markers: how do driver speed, lane position, number of encroachments, and driver comfort change as a function of pavement markings and markers? Sound analysis of human factor issues would require data collection on driver speed and lane position, and surveys of driver opinions for driver preferences with respect to comfort level. Addressing the gap in understanding the relationship between visibility and safety by studying crash data are needed to answer *how* safety is a function of visibility; however, controlled human factors research is needed to explain *why* visibility affects safety in sometimes unexpected ways. For example, a recent NCHRP study (4) found that snowplowable permanent raised pavement markers, despite providing improved delineation in comparison to painted pavement markings, were actually associated with decreased safety on tight curves. Human factors studies suggest that increases in speed with permanent raised pavement markers might be the mechanism underlying this unexpected effect.

iTRANS Consulting Inc. is currently investigating the gap #1 under NCHRP Research Project 17-28 which is focusing upon the relationship between visibility and safety, and the change in safety over time.

## Best Management Practices for Installation of Markings

Montebello and Schroeder (29) developed a summary of the best management practices based on Minnesota's experience, which include:

- The cost of striping is a function of the amount of material being applied, traffic control, and mobilization to and from the job site. Therefore, larger projects are generally more cost effective.
- Consider allowing adjacent communities to participate in hiring a striping contractor in order increase volume and lower overall costs.
- Evaluate the condition of the road before investing in more expensive striping materials in order to ensure maintenance or other construction activities will not shorten the life of the pavement marking investment.
- For waterborne paints, per-mix paint results in higher retroreflectivity performance over time than just dropping glass beads on the top of the paint. Pre-mix already has half the reflective beads in the paint. As the top surface glass beads are worn off, retroreflectivity degrades. However, pre-mix paint ensures that some beads will remain embedded in the paint and will get exposed with wear over the life of the line.
- Minimize workers' and drivers' exposure to traffic through proper coning and traffic control to ensure marking material stays on the road and create a safer work environment.
- Consider using temporary tape at construction zones. Temporary tape is more expensive but easier to remove than conventional materials with no grinding required.
- Apply lane marking materials just off the crown in order to reduce the potential of damage from snowplows.
- Always give significant consideration to storage, cleanup costs, and specialized training for personnel to deal with hazardous materials associated with striping.
- Refer to the Manual on Uniform Traffic Control Devices for appropriate sizing, location, and coloring information before striping.
- Clear all debris off the surface before striping.
- For best application quality, follow the manufacturer's directions.

## Safety

Recent research from Bahar et al.(4) has also found the safety effect of pavement markers explicitly tied to key aspects of road geometry and traffic volumes. Bahar et al.(4) collected crash, roadway geometry, and traffic volume data from six states (Illinois, Missouri, Pennsylvania, New York, Wisconsin, and New Jersey) from various time periods from 1991 to 2001, depending on the state. Bahar et al. conducted a before-and-after study specifically "to assess the safety effects of permanent raised pavement markers"(4). The before period consisted of 2-lane roadways, 4-lane undivided freeways, and 4-lane divided expressways without pavement markers, while the after period consisted of the same roads with markers. The retroreflectivity of markers, just like for markings, deteriorates over time. A study by Ullman (38) found that the retroreflectivity of many pavement markers dropped below minimum threshold after less than 6 months. The retroreflectivity of the markers remaining constant is necessary for a before-and-after study. Given that the after periods for the Bahar et al. (4) study ranged from 1 to 5 years depending on the state, Bahar et al. (4) selected states with careful monitoring and maintenance schedules. However, the Bahar et al. (4) survey results indicated that states replace markers in a cyclic pattern usually every 2 to 4 years, unless the field studies show 2 or more damaged permanent raised pavement markers in succession (38).

On 2-lane roadways, Bahar et al. (4) found that snowplowable pavement markers significantly *decreased* the occurrence of head-on crashes and wet-weather crashes. In addition, Bahar et al. (4) found that the safety benefit of snowplowable markers increased with higher traffic volumes. On the other hand, for 2-lane roadways, Bahar et al.(4) found that snowplowable pavement markers *increased* the number of nighttime crashes on sharp curves and roads with lower design standards, such as narrower pavement widths. On 4-lane freeways, Bahar et al. (4) found that snowplowable pavement markers *decreased* nighttime crashes and wet-weather crashes. An increased safety effect of snowplowable markers was also found with higher traffic volumes. In fact, Bahar et al.(4) found that snowplowable markers may not have been effective on 4-lane freeways with AADTs of less than 20,000 vehicles a day.

Pavement markings and markers are often installed to improve visibility specifically for those situations where visibility is particularly poor, such as at night and in poor weather conditions (e.g., rain, snow, and fog). Certain pavement markings have somewhat improved performances under adverse weather conditions compared with conventional paint markings. In order to quantify the safety effect and service life of all-weather pavement markings, Migletz et al. (27) conducted a large-scale evaluation working with the FHWA.

Over a 3-year time period (1994-1996), 85 sites in 19 states installed all-weather pavement markings on freeways, multi-lane cross sections, and 2-lane highways. In general, the all-weather markings used in the Migletz et al. study (27) consisted of the more durable (and more expensive) pavement markings, which included epoxy, methyl methacrylate, profiled methyl methacrylate, polyester, profiled polyester, profiled tape, thermoplastic, profiled thermoplastic, as well as conventional and waterborne paint combined with permanent raised pavement markers. No criteria for selecting sites with average crash frequencies were used, so the possibility of regression-to-the-mean exists. Thirty-three sites were eventually excluded from the safety evaluation because the researchers were unable to obtain crash or volume data for their sites.

A review of the literature reveals only two studies that examined the relationship between the visibility of markings and the number of crashes. In the first, Lee et al. (18) conducted a study of 50 locations in Michigan where the retroreflectivity of different types of markings over 3 years was measured and then compared with the number of nighttime crashes potentially associated with line visibility. One of the key difficulties in comparing visibility to the number of crashes is separating any seasonal effects from the delineation effects. There is no statistical methodology for separating the delineation and long-term effect from the yearly seasonal effect if, for example, all markings were installed on the same month each year. From an experimental design point of view, installation of markings and markers equally distributed throughout the year would be ideal. The reality is that northern states, such as Michigan, usually limit installation and restriping to the summer months, thus limiting the ability of statistical analysis to separate out the seasonal effect. Lee et al. (18) acknowledged this difficulty of seasonal bias but did not report what measures, if any, were taken. In the end, Lee et al. (18) were unable to identify any relationship between retroreflectivity and nighttime crashes.

The second study seeking to relate the visibility of markings to crashes, Abboud and Bowman (1), collected retroreflectivity readings on 520 miles of rural highways in Alabama over a 4-year period and compared them with the number of nighttime crashes potentially associated with line visibility. In their analysis, Abboud and Bowman (1) assumed linearity by using crash rates instead of frequency counts. However, expected accident frequency is not linearly proportional to traffic volume. In other words, the use of accident rates can be misleading and can produce conclusions that may be untrue. In addition, Abboud and Bowman (1) did not address seasonal effects or apply any analysis methods that could minimize a seasonal bias. Abboud and Bowman (1) compared the long-term crash rate to the average crash rate for the study period to identify 156 mcd/m$^2$/ls as the minimum acceptable retroreflectivity threshold for maintaining a crash rate below the study period's average. This conclusion was highly dependent up time of restriping of the markings in that one would expect that newly striped roads would have different crash rates than poorly maintained roads. Abboud and Bowman (1) admitted that the number of years of post-striping data for all roads was not equal, and therefore data from a road with only 1 year of post-striping data would have a different retroreflectivity average than data from a road of 3 years of post-striping data.

Numerous safety evaluations of longitudinal marking have been published in the literature. Nearly all published studies evaluating the safety impact of marking have used variants of the before-and-after design, where the crash history of a road in a before period is compared with the period after a change (e.g., installation of edgelines, change in the type of pavement materials) has been made. Sometimes comparison or control locations are used to identify any existing crash trends over time.

To summarize, the performance of pavement markings in terms of retroreflectivity over time is understood to follow basic patterns that can be modeled. Driver preference is for markings to have retroreflectivity levels greater than 100 mcd/m$^2$/lux. What remains unknown is what effect the change in retroreflectivity has on driver safety.

## Conclusions

There are agencies that operate a pavement management system, which incorporates pavement markings and markers as a minor item in a very large structure, but very few agencies have implemented an exclusive pavement marking management system. Typical criteria used to evaluate the cost-effectiveness of pavement markings include: durability, retroreflectivity, and cost. Cost can become a critical factor when selecting pavement marking materials for installation. As a result, preventive maintenance and good budget planning become essential.

Some state agencies have developed or integrated decision-making tools that assist in evaluating the multiple criteria regarding the life and serviceability of a pavement marking.

Pavement markings are considered by many to be a minor maintenance treatment (19) and as a result are not regarded as an integral part of many pavement management systems. Numerous reports that deal with pavement management systems (6,7,5,12,21), however are often too macro and give no additional insight into the area of pavement markings and markers. They illustrate that there is a need to improve the current management systems and promote the important role of markings in an adequate pavement management system.

Waterborne paint is traditionally the least expensive pavement marking material when incorporating only material and installation costs in the life-cycle cost analysis. However, several other factors can have an impact on the economics of pavement markings, such as extent of inconvenience experienced by the traveling public during marking installation (cost of delay), tort liability, quality and extensiveness of installation, and cost of life of road users and work crews. As a result, more durable markings can become the most beneficial material alternative. A benefit-cost analysis incorporating all the aforementioned factors should assist in determining the true cost-effectiveness of the selected marking materials.

Safety impacts of the visibility of markings and the number of crashes are limited in their documentation; but there have been two specific studies that examined this relationship. One of the key difficulties identified in comparing visibility to the number of crashes is separating any seasonal effects from the delineation effects.

A thorough analysis of edgelines using a before-and-after methodology, where specific control locations were selected so the crash rates were directly comparable to other similar road types, concluded that crashes actually increased on curves after edgelining and that the effect of markings was dependant on curve radii (8). Another study (14) found that centerline and no-passing zone markings actually increased the amount of crashes on low-volume roads. A similar research study (4) found that the use of snowplowable pavement markers yielded the same results as the edgeline and centerline pavement markings. These counter-intuitive results occurred mainly from the hypothesized idea that pavement markings or increased delineation (increased detection distance) may help increase the driver’s comfort level, resulting in lower driver awareness and higher traveling speeds.

Pavement markings are unlike many other engineering safety treatments in that the treatment is continuously changing. Agencies tend to specify levels of minimum retroreflectivity standards two ways: by recognizing that increased retroreflectivity equals increased visibility for drivers under nighttime conditions, and that increased visibility equals increased safety for road users. While the first assumption has been validated by field data, with visibility being defined as detection distance, increased detection distance has not always meant an increase in safety, especially for roads with lower design standards. The key to understanding the safety impact of marking delineation is to understand the interaction between driver response, delineation, road geometry, and traffic volumes.

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