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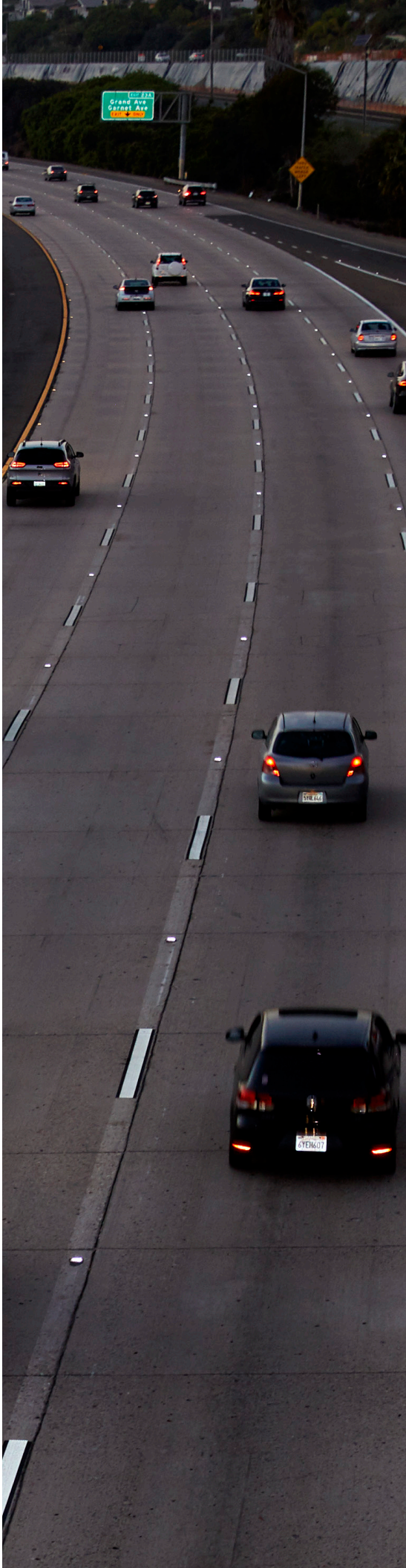
Improving Pavement Markings

for Humans and Automotive Cameras in Challenging Driving Conditions

authored by

Dr. Matt Wilding, Dr. Kris Hansen, Dr. Susannah Clear



Executive Summary

In the United States alone, over 35,000 lives are lost each year in traffic accidents. Many of these accidents (>20%) occur during inclement weather, mostly on wet roadways (1). Experts estimate that currently available assisted-driving technologies such as lane keep assist (LKA) and lane departure warning (LDW) could have a significant impact on the number of accidents and, significantly, fatalities. For example, universal use of LKA/LDW technologies alone could save 7,500 lives yearly (2). Many of these driver-assist technologies are based on automotive cameras that function best with lane markings that have a high luminance (brightness) and a strong, consistent contrast against the background (3,4). For human drivers, studies indicate that brighter pavement markings can reduce crashes, especially on wet roads. Specifically, one study found that pavement markings with wet retroreflectivity performance reduced crashes on wet roads by 25% (4).

Providing consistent, reliable lane guidance in all conditions, day and night, wet and dry is a top priority for Traffic Engineers, Technology Officers, Department of Transportation Product Qualification Personnel, Pavement Marking Application Contractors, and anyone involved in the road planning and building process who aims to create safer, more mobile roads for the present and the future. This effort becomes more complicated with the increasing popularity of assisted driving systems that rely on sensors like optical cameras to keep vehicles positioned properly in the lane. As the percentage of vehicles equipped with these sensors grows, lane guidance systems need to work well with human- and machine-vision.

For many years, the challenge of providing pavement markings that can be seen at night has been improved with the use of retroreflective optics, including the addition of retroreflective glass beads to liquid pavement markings and the use of reflective sheeting on raised pavement markers (RPMs). These retroreflective optics are designed to return light from a vehicle's headlights back to the driver, making the pavement markings visible at night.

However, wet and rainy conditions create additional challenges for pavement marking visibility. Due to the refractive index of water, wet pavement markings spread light out in a much broader, weaker cone of returned light than dry pavement markings. As a result, the wet pavement marking returns only a small amount of the light from the vehicle's headlights to the driver. This challenge makes many of the existing retroreflective pavement marking solutions ineffective in wet conditions whether the driver is a human or a machine. More on this will be covered in later sections of this whitepaper.

As we look toward a future of vehicles with varying levels of automation—including vehicles equipped with advanced driver assistance systems (ADAS) and fully connected and autonomous vehicles (CAVs)—

highly detectable, consistent and reliable pavement markings remain an important feature of the roadway, providing primary and redundant features that can be used to support these advanced features. Automated and autonomous vehicles rely on machine vision systems—networks of sensors and cameras providing input to a vehicle computer— the collected input provides situational awareness and may help the vehicle appropriately react to surroundings. For these systems to provide safe and effective lane departure warning and lane keep assistance, many benefit from pavement markings that are highly detectable, especially in challenging driving situations such as at night and in the rain, a particularly challenging environment that is the focus of this paper.

This whitepaper will examine typical retroreflective pavement marking solutions and provide an overview of the new 3M™ Connected Roads All Weather Elements. We will then present results of our study on the performance of existing retroreflective pavement markings solutions and the new 3M™ Connected Roads All Weather Elements in dry, wet continuous and wet recovery conditions at various stages of wear. The study demonstrates that 3M™ Connected Roads All Weather Elements are more durable than the existing solutions to which it was compared; further, 3M™ Connected Roads All Weather Elements provide higher retroreflectivity in wet and wet recovery conditions.

The Challenge: Consistent Lane Guidance in All Conditions

Consistent, clear and cost-effective lane guidance in all conditions – good and bad - has been a top priority and an ongoing challenge for road planners. Solutions have evolved from simple painted white lines in the early 1900s to the variety of retroreflective liquid pavement markings with drop-on optical components, pavement marking tapes, and raised pavement markers (RPMs) on the roads today. These options require that road planners evaluate the particular features of the roadway, as well as the safety benefits of a lane marking solution versus the costs.

Although any pavement marking solution may be adequate when driving conditions are perfect, driving conditions such as nighttime or rain can be challenging. For example, due to the higher refractive index of water when compared to air, most retroreflective pavement markings will have reduced visibility for drivers and automotive cameras when they are wet, which can reduce the effectiveness of some pavement marking solutions. Since studies indicate the majority of weather-related crashes occur on wet roads (1), it is important to identify a lane marking solution that provides good visibility in these conditions.

Retroreflective liquid pavement markings were first developed to increase lane guidance visibility at night. The most common liquid pavement markings consist of spherical glass beads (optics), typically with a refractive index (RI) of 1.5, dropped onto the lane marking and attached using a binder. This binder contains a pigment (usually yellow or white) to provide color and serve as a reflector.

As light from a vehicle's headlamps hits each optic, the light bends, reflects off the pigment on the backside of the optic, and bends again as it passes out of the optic. This creates a cone of light. When the optics are illuminated by headlamps, a sufficient portion of the light returns to the driver and the vehicle, making the optics and the pavement marking visible to the driver or the camera. The RI of both the optic and the air surrounding the optic determine how much the light bends, and whether enough light returns to the driver or camera to be highly visible in nighttime conditions.

However, when it is raining and the glass beads in the pavement marking become wet, or when water covers the glass beads, the optics are no longer surrounded by air, but instead are surrounded by water. Water has a higher RI than air, causing the light to enter and exit the glass optic at different angles. As a result, the light is spread out in a much broader but weaker cone, and very little light is returned toward the vehicle. This substantially reduces the visibility of the pavement marking to both human and to the optical camera working to provide lane guidance.

Studies indicate that vehicles equipped with ADAS systems like Lane Departure Warning Systems and Lane Keep Assist Systems can help mitigate crashes associated with lane drift (2), but only if the system is engaged and able to detect the lane markings. In some vehicles, if the sensor cannot consistently detect the lane markings, it warns the driver and then turns off. Lane marking solutions that provide more robust

delineation and better visibility to automotive cameras in wet conditions should expand the conditions during which the advanced driving features can operate effectively to protect roadway users (5,6,7).

Machine vision systems and human drivers function best with pavement marking solutions that deliver consistent, reliable detection in good driving conditions and in challenging conditions like wet roadways.

Optical cameras, in general, and automotive cameras, specifically, work best with pavement markings that have both a high luminance and a high contrast ratio. Contrast ratio is a measure of the luminance or brightness of the pavement marking compared to the adjacent surface, usually the roadway. A higher contrast ratio helps the marking stand out from the surroundings. Some lane detection algorithms used in ADAS, include calculation of gradients in pixel intensity for each point in the image, followed by application of a threshold so that only pixels where the gradient is greater than that threshold level are retained for feature extraction (3). Smaller gradients resulting from less contrast between marking and roadway may make the markings difficult to differentiate and thereby increase the likelihood of a false negative.

Existing Pavement Marking Solutions

Historically, a variety of retroreflective liquid pavement marking solutions have been tested and employed to increase visibility in challenging conditions such as at nighttime and in wet conditions. Although generally more effective than paint without retroreflective optics, each of these solutions has limits that should be addressed in planning the roads of the future.

Let's examine a few of the existing pavement marking solutions.

1.5 Refractive Index Glass Beads

Glass bead optics, which include the 18/50 blend (Utah Spec), are perhaps the most common and well-known retroreflective optics. To make a pavement marking with these optics, retroreflective glass beads with an RI of 1.5 are dropped onto the liquid pavement marking binder before it hardens. The glass beads are typically embedded in the binder to a depth of around 50-60 percent of their diameter.

When light from a vehicle's headlights hits the retroreflective glass beads, it is bent toward the back of the bead, reflects off pigment in the bonding agent (which typically has yellow or white pigment added to affect the color of the pavement marking) and a percentage of the light is returned back to the light source (the vehicle headlights).

This solution provides suitable initial retroreflectivity in most dry situations. However, because water has a different RI than air and thus bends light differently, 1.5 refractive index glass beads have very low light return in wet conditions, including when it is raining and after rain when water is still surrounding the optics. This limitation challenges both human drivers and automotive cameras from consistently detecting pavement markings in wet conditions.

Large & Small Glass Beads in a Double Drop

One solution that has been used to mitigate the impact of water on glass bead pavement markings is to apply 1.5 RI glass beads of different sizes in a double drop—often a Type IV & Type I double drop. The term double drop refers to the application process. The binder is applied to the road, followed by an application of large beads and an application of small beads.

The advantage of this solution is that the larger beads are less likely to be fully submerged in water that has pooled on the road, preserving the air-bead interface to continue to provide retroreflectivity.

However, if the water becomes deep enough to submerge the large glass beads during a heavy rain event or puddling), large glass beads suffer the same drawbacks as small glass beads resulting in reduced retroreflectivity and reduced visibility. Consequently, large glass beads have limited efficacy during heavier rainfalls.

3M All Weather Elements

3M™ All Weather Elements, introduced over a decade ago, are engineered to deliver true wet and dry retroreflectivity. These elements consist of beads with two different RIs to provide a complete retroreflective optical package even before they are applied to the liquid pavement marking. Unlike retroreflective pavement markings that are “manufactured” on the roadway (where the optics are dropped and allowed to sink into a binder), 3M™ All Weather Elements embed optics into a binder under controlled conditions to minimize variability of retroreflective performance.

For optimized dry retroreflectivity, 3M™ All Weather Elements feature 1.9 RI toughened beads. Because they have a higher RI than conventional glass beads, 3M toughened beads bend the light more than 1.5 RI beads, resulting in a narrower cone of retroreflected light. This enables the optics in the 3M™ All Weather Elements to deliver peak retroreflective efficiency in dry conditions. With recommended drop rates on pavement marking binders, 3M™ All Weather Elements produce brighter pavement markings than the glass beads alone with increased visibility for human drivers and more consistent detection of pavement markings both near the vehicle and at longer distances suited for detection by automotive cameras.

For true wet retroreflectivity that works even when the optics are covered with a layer of water, 3M™ All Weather Elements also contain ultra-high 2.4 RI microcrystalline ceramic beads. The 2.4 RI of these beads is the highest practical refractive index achieved to date by 3M. 3M’s internal lab testing of 3M’s beaded pavement markings with exposed optics demonstrate greater wet retroreflectivity levels than the previous markings.

The beads used in 3M™ All Weather Elements are also more durable than conventional glass beads. The beads were engineered to provide better retroreflectivity than conventional glass beads after blasting with abrasive media.

Each element is designed with increased diameter compared to the high index beads alone, making the elements stand higher out of the liquid marking, thereby increasing the effectiveness of the 1.9 RI optics in wet recovery conditions. Compared to conventional beads that are embedded directly into the paint the face of a 3M™ All Weather Element presents multiple beads to incoming light on a raised surface on the horizontal road surface. This multitude improves the retroreflectivity of each individual optic by capturing and reflecting more light than conventional glass beads.

Like all optics, 3M™ All Weather Elements wear under heavy use. However, unlike glass elements, as 3M™ All Weather Elements age and begin to wear, the core is exposed, causing the element to appear darker or turn brown over time. This can give a white pavement marking a darker appearance, reducing the brightness and the contrast for human drivers and automotive camera systems. 3M has addressed this challenge by developing a better pavement marking solution.

Proposing a Better Pavement Marking Solution

New 3M Connected Roads All Weather Elements offer the same 1.9 RI and 2.4 RI beads for peak efficiency and visibility in both wet and dry conditions, along with the engineered composition to improve bead durability.

To address the drawbacks of existing pavement marking solutions, particularly when considering performance in adverse conditions that challenge both human drivers and automotive cameras, 3M has developed a new pavement marking solution to deliver the same optics and high refractive index of current 3M™ All Weather Elements, while offering greater durability and a longer lifespan at peak efficiency and brightness. Such a solution could provide greater retroreflectivity than the current 3M™ All Weather Elements and conventional glass-beaded liquid pavement markings in adverse conditions, resulting in better visibility for human drivers and for automotive cameras over a longer performance lifespan.

The primary difference between the new 3M™ Connected Roads All Weather Elements and the existing 3M™ All Weather Elements is in the core of the element. With 3M™ Connected Roads All Weather Elements, the dark core has been replaced with a core comprised of a white- or yellow- colored composite material. The 1.9 RI or 2.4 RI beads are bonded to the core. The colored core in 3M™ Connected Roads All Weather Elements, as shown in the right of Figure 1, enables each element to remain truer to the marking color even

as it ages. The composite core also contains intermixed glass beads that become exposed as the surface is ablated. Once exposed, the intermixed beads enable better later-life retroreflective performance compared to the existing 3M™ All Weather Elements. The composite core is also more compliant than the previous core, which provides improved fracture resistance compared to the existing 3M™ All Weather Elements. Thus, 3M™ Connected Roads All Weather Elements maintain high performance over a longer time than the existing All Weather Elements for an effective, more durable solution.

By creating optics that deliver true wet and dry retroreflectivity with greater durability and a longer useful life, 3M is working to provide improved pavement markings for human drivers and for automotive cameras. The 3M™ Connected Roads All Weather Elements work to keep roads safer by providing infrastructure solutions that aid both human drivers and automotive cameras in some of the most challenging driving conditions.

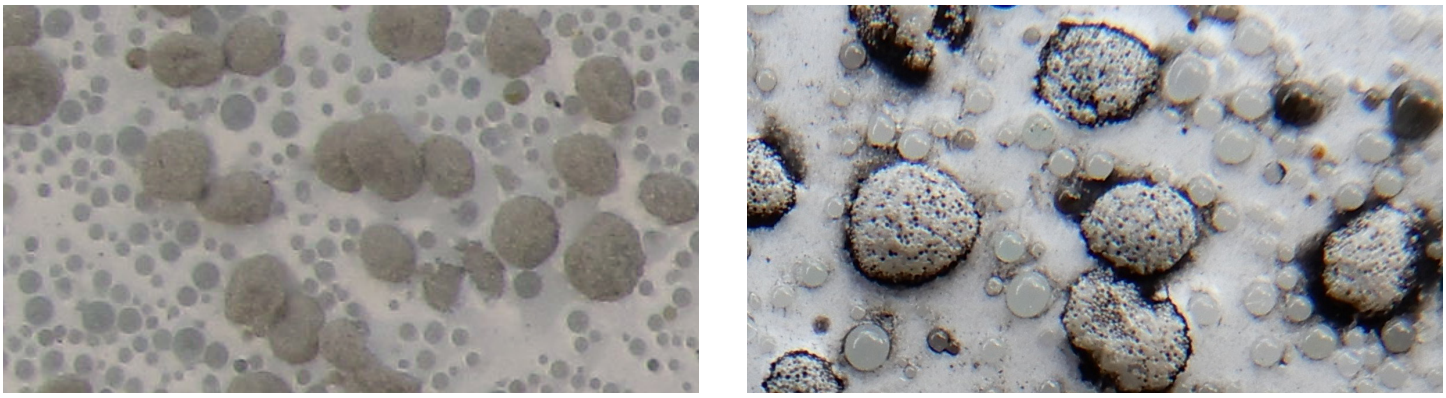


Figure 1. 3M™ Connected Roads All Weather Elements: freshly-installed (left), and after one year in the wheel track of a southern US road (right).

Testing the New Pavement Marking Solution

To put our new 3M™ Connected Roads All Weather Elements to the test and compare them to several existing pavement marking solutions on the market, we set up an experiment at the 3M test facility in St. Paul, Minnesota. To simulate real world conditions as closely as possible, we tested each pavement marking solution in dry conditions, conditions of continuous wetting (wet continuous or rain-like) and conditions of recovery after wetting (wet recovery). We tested the pavement markings when they were new and at various stages of wear.

The Experiment

For the study, retroreflective material samples (beads and elements) were coated on 4-foot long aluminum panels. The samples were bound to the aluminum panels using 3M™ Liquid Pavement Marking Series 5000 polyurea.

We tested the following types of retroreflective pavement marking materials under a variety of conditions:

- 1.5 refractive index glass beads, 18/50 Blend (Utah Spec)
- 1.5 refractive index glass beads, Type IV & Type I double drop
- 3M™ All Weather Elements Series 90 with 18/50 blend glass beads double drop
- 3M™ Connected Roads All Weather Elements Series 50 with 18/50 blend glass beads double drop
- 3M™ Connected Roads All Weather Elements Series 90 with 18/50 blend glass beads double drop

Wear

We artificially wore pavement markings to test their durability and effectiveness over time. To simulate road wear, the pavement markings were "aged" using 3M's Vehicle Wear Simulator (described in U.S. Patent No. 5,777,791).

The tires of the simulator were coated with 3M™ Surface Prep Adhesive 60, and then covered with sand (granules approximately 600 to 2000 microns in diameter) to accelerate the wear process. The tires were recoated whenever enough of the sand had fallen off the tires to slow the wear rate. Sample sets were run at the same time so each sample in the set would receive an identical wear history. The control sample (3M™ All Weather Elements Series 90) was checked periodically. The process was stopped when the control sample reached the desired wear level.

Three sample sets with different wear histories were created: New, Half, and End

- New – unworn
- Half – worn until 3M™ AWE Series 90 sample was at about half the initial dry retroreflectivity measurement value
- End – worn until 3M™ AWE Series 90 sample was between 100 and 200 mcd/m2/lux dry retroreflectivity

Coefficient of Retroreflected Luminance (R_L) Measurement

The coefficients of retroreflected luminance of the sample panels were obtained with a Delta LTL-X retroreflectometer following ASTM E1710 for dry measurements, ASTM E2832 for wet continuous (raining) measurements, and ASTM E2177 for wet recovery measurements.

Image Collection

Camera images were collected with a Point Grey Chameleon 3 camera with a 16mm lens, inch sensor, 30-degree horizontal field of view, and 26-degree vertical field of view. The camera was mounted 53.5 inches above the ground. Images taken with the Point Grey camera were set to be collected at full auto exposure settings. The algorithm for auto exposure automatically controls either or both the exposure and the gain to achieve a specific average image intensity. The ranges of allowed values of auto exposure, auto shutter, and auto gain were not limited.

Calibrated luminance measurements of pavement markings were performed with a Radiant Vision Systems Radiant ProMetric I-16 with a 200 mm e-lens. The ProMetric had an 8-degree horizontal field of view and a 5-degree vertical field of view and was also mounted 53.5 inches above the ground.

In an indoor rain simulator, images were collected to simulate three road conditions:

- Dry (representing the conditions used in ASTM E1710)
- Wet Continuous / Raining (representing the conditions used in ASTM E2832)
- Wet Recovery (representing the conditions used in ASTM E2177)

The horizontal distance from each camera to the markings was 64 feet. The light source for each camera measurement was a 500-watt halogen bulb providing 8000 lumens mounted in a portable work light. The bulb height was 43 inches above the ground.

Sobel edge contrast was determined using Canny edge detection and the procedure described in Whitney et al. [3]

The Results

The study demonstrated that new 3M™ Connected Roads All Weather Elements and existing 3M™ All Weather Elements both delivered better retroreflectivity compared to the other optics in the study during nighttime dry and in wet conditions. With the 3M™ Connected Roads All Weather Elements, there was a marked improvement over the lifespan of the element compared to the existing 3M™ All Weather Elements, demonstrating the durability of the retroreflectivity of these new elements.

As shown in Figure 2, 3M™ Connected Roads All Weather Elements delivered superb retroreflectivity in wet continuous and wet recovery conditions when compared to existing solutions (including 3M™ All Weather Elements, the Type IV & Type I double drop, and the 18/50 1.5 glass bead blend (Utah Spec)). The 3M™ Connected Roads All Weather Elements continued to provide higher retroreflectivity (relative to existing solutions) through the mid- and end- of life conditions in the 3M™ Vehicle Wear Simulator, demonstrating that the durability and performance of 3M™ Connected Roads All Weather Elements' lasts over the lifespan of the product.

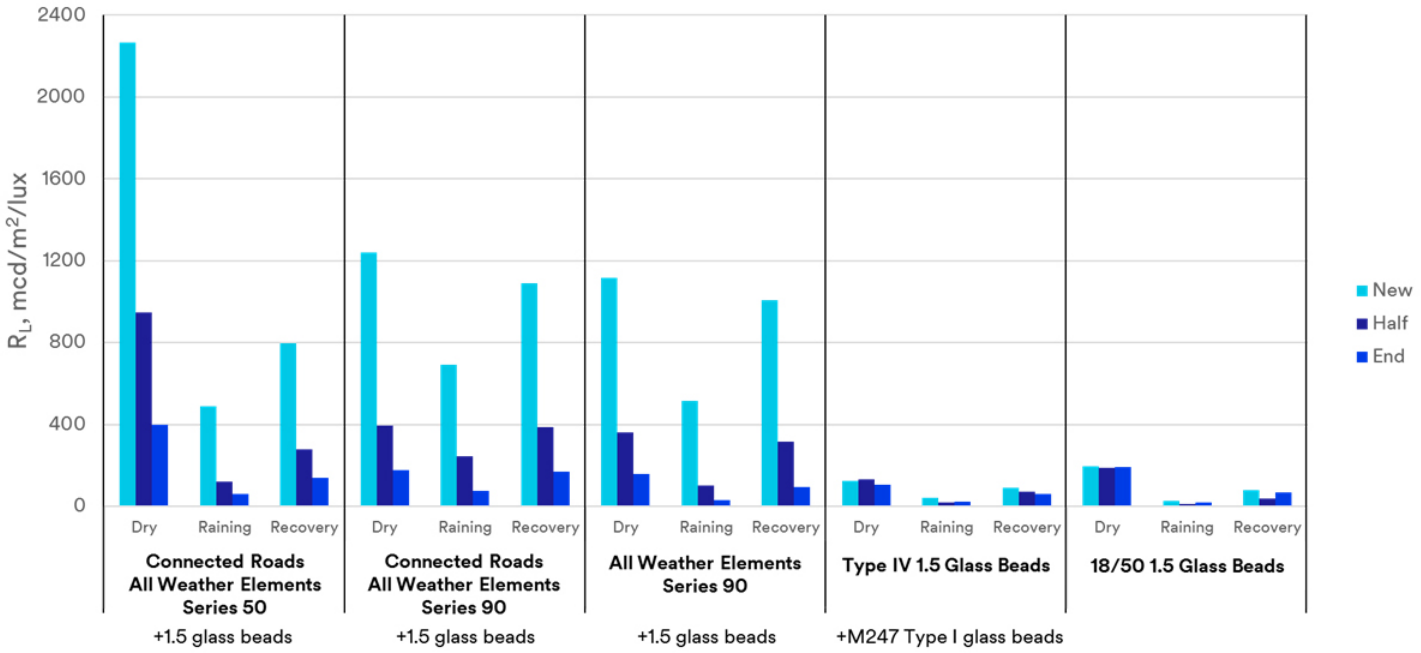


Figure 2. Pavement Marking Retroreflectivity in Dry, Wet, & Wet Recovery Conditions (New, Half, and End Wear Conditions in 3M Vehicle Wear Simulator)

Additionally, when compared to the 18/50 1.5 RI glass bead blend (Utah Spec) and the Type IV & Type I double drop glass beads, the 3M™ Connected Roads All Weather Elements Series 50 delivered the best luminance (Figure 3) and contrast (Figure 4) in ideal conditions (dry roads, new elements). New 3M™ Connected Roads All Weather Elements Series 90 offered the best luminance and contrast in wet conditions and the highest contrast in wet recovery conditions. The 3M™ All Weather Elements Series 90 delivered the highest luminance during wet recovery conditions but the luminance of 3M™ Connected Roads All Weather Elements was at a similar level and at the "half" wear condition, was higher.

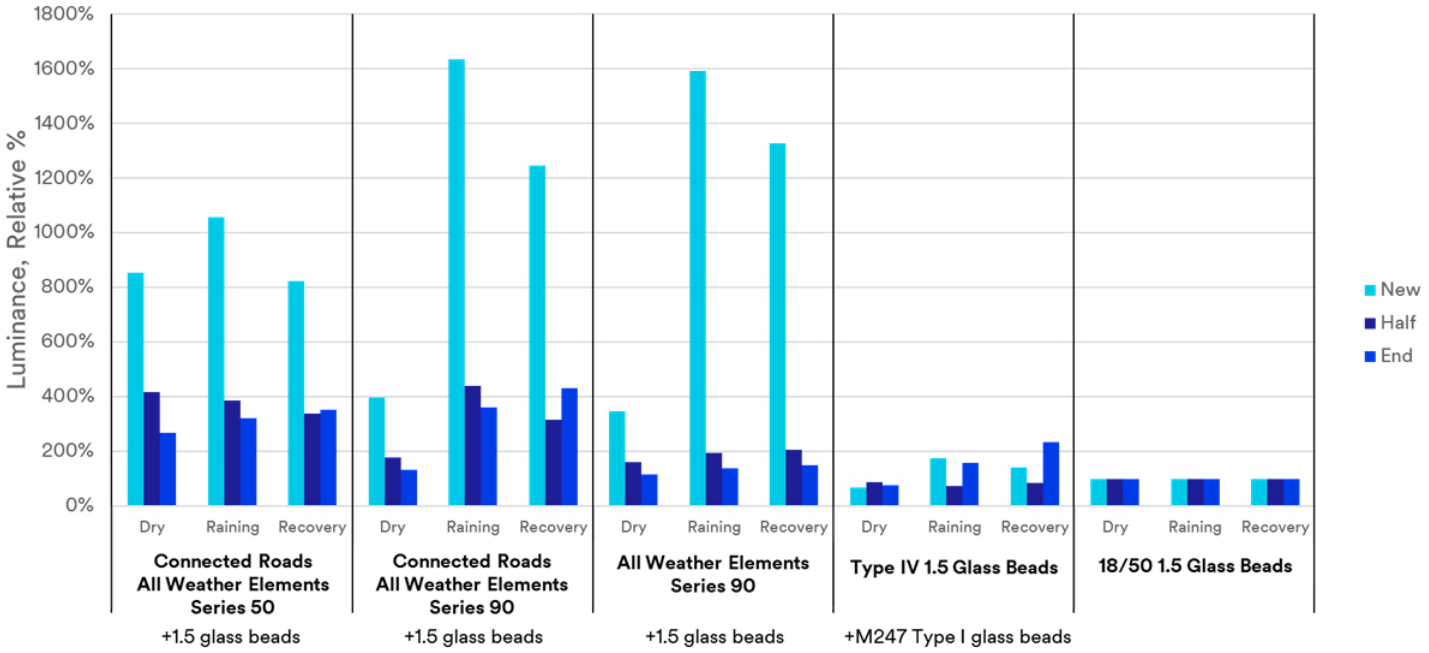


Figure 3. Luminance Relative to 18/50 1.5 Glass Beads

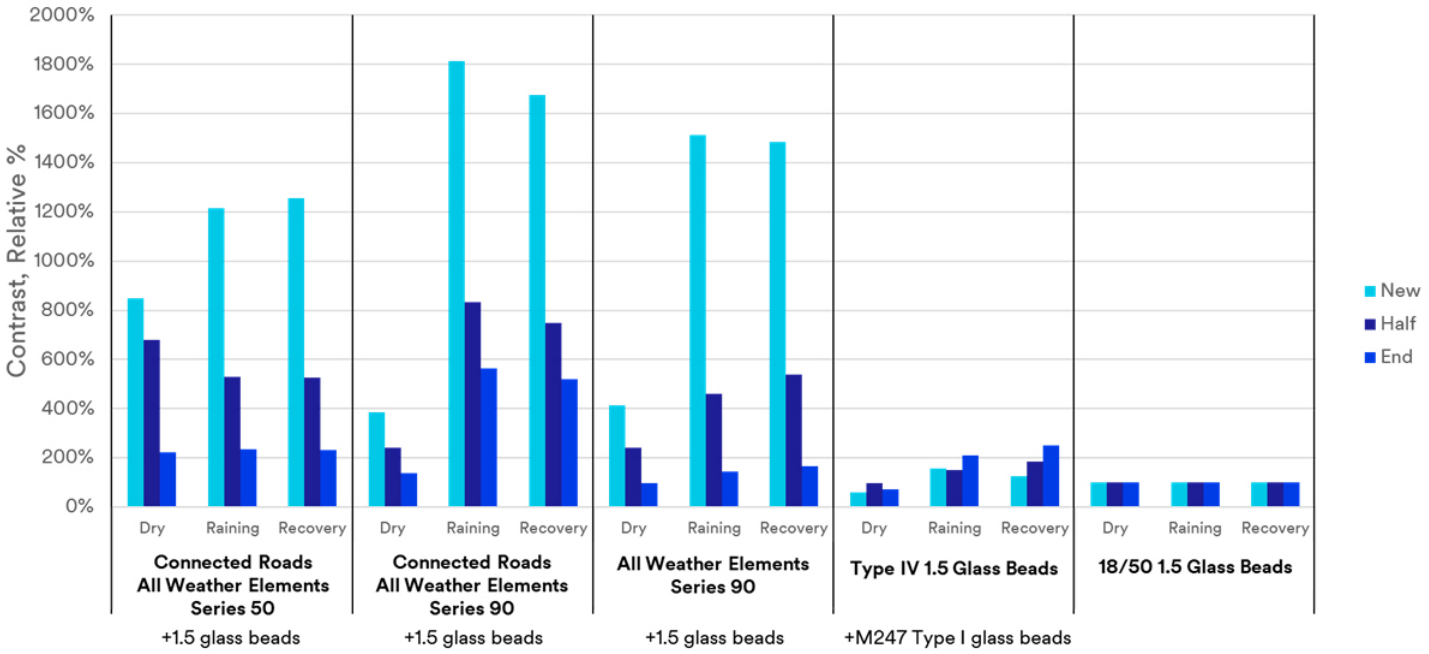


Figure 4. Contrast Relative to 18/50 1.5 Glass Beads

Of particular interest is the higher luminance and contrast delivered by 3M™ Connected Roads All Weather Elements throughout the simulated lifespan of the product. Even at the end of life condition in the 3M™ Vehicle Wear Simulator, the 3M™ Connected Roads All Weather Elements continued to provide higher luminance and contrast compared to the 18/50 1.5 glass bead blend (Utah Spec) and to the Type IV & Type I double drop glass bead blend. The 3M™ Connected Roads All Weather Elements Series 90 offered over 3-fold increase in luminance and over 5-fold higher contrast in both wet and wet recovery conditions.

Collectively, these data demonstrate that 3M™ Connected Roads All Weather Elements perform better than a conventional glass bead solution in almost every variant of challenging conditions studied. Further, 3M™ Connected Roads All Weather Elements maintain higher performance levels over long periods of wear.

A Pavement Marking Buyer's Guide

When planning your next road infrastructure project, you need to find ways to continue building safe, mobile roads for human drivers as well as the vehicles equipped with automotive cameras that support machine vision systems. To help increase the safety of your roads, invest in pavement markings that deliver reliable retroreflectivity in common and challenging conditions, including day and night, wet and dry. Optimize your roads for the present reality of human drivers and for vehicles equipped with automotive cameras while preparing for a future when human drivers will be sharing the roads with vehicles that have increasing levels of automation.

As you're considering your liquid pavement marking options, here are some factors to keep in mind:

- Retroreflectivity — Pavement markings that deliver high retroreflectivity may help keep your roads safer by providing both human drivers and automotive cameras with consistent and reliable lane markings.
- Wet Retroreflectivity — Most conventional optics systems in liquid pavement markings offer retroreflectivity in ideal, dry conditions. To build roads that provide functionality when conditions are not ideal, for example at night and in the rain, install pavement markings that deliver reliable retroreflectivity in these conditions. High wet retroreflectivity benefits both humans and automotive cameras.
- Contrast – Pavement markings that provide high, consistent contrast in all driving conditions will help provide the best environment for achieving optimal performance of automotive cameras.
- Durability — Durable pavement markings that last longer and maintain high retroreflective performance (wet and dry) and high contrast over the lifespan of the marking can help reduce costs for upkeep and replacement.
- Materials - Some materials offer greater resilience and robustness than others. Retroreflective pavement markings that use beads specially formulated for durability provide longer lasting performance than conventional glass beads.

Conclusions on Delivering Consistent Lane Guidance for Human Drivers and Automotive Cameras in Challenging Conditions

Through our internal study, these data demonstrate that 3M™ Connected Roads All Weather Elements deliver greater luminance and contrast than previous pavement marking solutions, resulting in superior retro-reflectivity, in dry and wet conditions. This performance difference becomes especially significant in wet continuous and wet recovery conditions. 3M™ Connected Roads All Weather Elements deliver higher performance throughout the useful life of the pavement markings, demonstrating the durability and resilience of the new 3M™ Connected Roads All Weather Elements.

Installing 3M™ Connected Roads All Weather Elements in your next roadway infrastructure project may provide greater lane guidance visibility in common and challenging conditions, for human drivers and for automotive cameras. Based on the durability data presented here, 3M™ Connected Roads All Weather Elements may provide superior performance and require less maintenance and less frequent replacement.

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3M

Transportation Safety Division
3M Center, Building 225-4N-14
St. Paul, MN 55144-1000
1.800.553.1380