3.00 Lines & Signs - Delivering Safer Roads for All Drivers

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ABSTRACT:

This paper will be presented in two parts. First will be an overview of truly wet reflective pavement marking systems These are materials that are comprised of a combination of dry reflective glass beads and advanced microcrystalline ceramic reflective lenses to provide continuous dry reflectivity.

The second part of this paper will discuss the principles behind the design decisions made when developing a new retroreflective sign sheeting. Retroreflective sign sheetings are made using a range of reflective technologies including enclosed glass beads, encapsulated glass beads and more recently cube corner prismatic materials.

Prismatic lens technology has afforded manufacturers the ability to construct reflective sheeting to meet specific driver needs, by modifying lens geometry to control the divergence of the retroreflected light. For the driver, correctly controlled divergence translates into higher sign luminances & thus improved sign legibility.

Lines and Signs – Delivering Safer Roads for All Drivers

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Introduction

The contribution of effective signage and pavement markings to road safety outcomes is well established. Improving lines and signs has been one of the methods used by Australia and New Zealand's Road Authorities to deliver the continued reduction of road user fatalities and injury over the past 20 years. These improvements have been realised in a number of ways for both assets. For pavement markings, best practice has focussed on the impact brighter, wider and more durable pavement markings can have in effecting lasting road safety change. In the case of signage, better understanding of sign placement for optimum driver utility and sign legend layouts & size has resulted in improved sign legibility. Furthermore continual technological advances in both areas have enabled higher performing materials to be deployed to increase the useful working life of the asset, lengthening the cycle of replacement or remarking.

While it may seem to some observers that line marking and static signing technology have reached a point of stagnation, this is far from true. Manufacturers have moved beyond the paradigm of development for development's own sake to instead consider the driving needs of road users when designing a new material. Well known examples of this are the application of large, high refractive index glass beads to create brighter lines to aid the driver and durable fluorescent signs to help pull safety critical signs out of a cluttered, daylight environment.

Two recent advances in pavement marking and signing are discussed in this paper. The first involves the use of very high refractive index, composite reflective elements as an additive to roadmarking paint. These high index elements function to give the pavement marking true wet reflectivity, resulting in a line marking that is effective in all weather conditions. The second is the driver focussed design and development of a "full cube" microprismatic retroreflective sheeting. This novel new construction permits the manufacture of reflective signage that returns almost twice as much light to the driver in comparison to current technologies. This extra light can be used to provide more luminance to the operators of vehicles with wider observation angles, such as trucks, without compromising the driving experience in narrow observation angle vehicles such as cars.

ALL WEATHER PAVEMENT MARKINGS

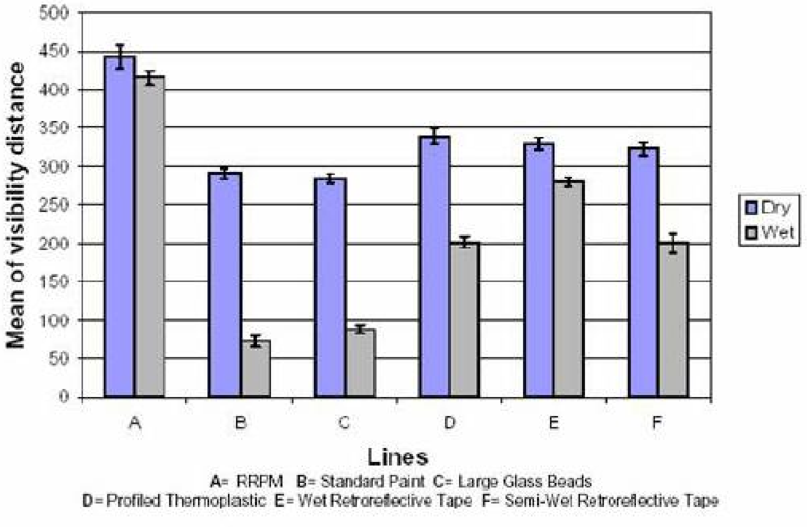
Introduction

It should be obvious to all that in order for a pavement marking to be effective it must first be visible. During the day, this is generally achieved through the use of white paint or polymer composite material to form the structure of the line and provide contrast between the black roadway and the white marking. Modern pavement markings also have glass beads embedded in the exposed surface of the material to provide retroreflectivity during night time hours. These glass beads act by reflecting the light from an approaching vehicle's headlights back in the direction of the vehicle; this is retroreflectivity.

Retroreflectivity is crucial property for pavement markings because drivers require extra guidance during the night. Ninety percent of the information required by a driver is acquired visually. During daylight hours drivers take visual cues from the horizon, trees, buildings and the general topography along with the road signage and markings. At night on the other hand, many of these visual cues disappear and the driver must rely far more heavily on line markings and signage. Danger is hidden in the darkness: a sharp curve, an intersection, a truck making a wide turn, or a car parked on the side of the road. The consequences can be costly.

Performance of Current Pavement Markings in Wet Conditions

It is indisputable that pavement markings with embedded glass beads are an effective system in most conditions. However it has long been known that in rainy weather at night time, traditional glass bead pavement markings exhibit severely reduced reflectivity. From a road safety perspective, this is somewhat paradoxical as it is exactly in these conditions that motorists need the most assistance from the road infrastructure. Figure 1 shows a comparison of the dry & wet visibility of various pavement marking systems[1].



Source: *Wet Night Visibility of Pavement Markings*, Virginia Transportation Research Council, October, 2004

Figure 1 Visibility distance for various pavement marking systems, wet and dry.

Historically, wet visibility has been achieved through the use of retroreflective raised pavement markers (RRPM's) to delineate lane and edge lines. Figure 1 supports this, as RRPM’s have been demonstrated to be equally visible in dry or wet conditions. While RRPM’s are effective in these conditions, they are not the entire solution. Widespread installation of RRPM’s is costly and labour intensive. Furthermore, the need to remove and reinstall broken or old RRPM’s introduces the possibility of pavement surface degradation. These issues make RRPM’s less than ideal for use in applications other than spot delineation.

The most commonly employed means of improving line marking wet visibility is the use of large glass beads. The principle behind this is that a larger bead will facilitate draining of the water from the lens surface, or that the bead will protrude above the water film on the road. This approach is fairly cost effective, and in light rain showers it is effective enough. However, during heavy or even moderate rainfall events water is often deposited on the surface faster than it can drain. In such conditions there is not adequate recovery time for the pavement marking to be effective, which is why the wet preview distance for large beads in the previous figure is so much lower than in the dry state. This particular study also found that large glass beads were only marginally better than small beads in the study wet conditions.

Considering the other systems depicted in this figure, wet reflective tape, semi-wet reflective tape and profiled thermoplastic, only the last is used to any degree in Australia. Increasing use of wet reflective pavement marking tape has been occurring in New Zealand but this has not yet begun to find favour in Australia. Profiled thermoplastic markings also function by removing the glass bead optic from the film of water, therefore they also must be considered a wet recovery treatment rather than a true wet reflective system. While the initial performance of a profiled thermoplastic marking may be impressive, ongoing wet and dry visibility depends completely on the quality of intermix optics used and this has traditionally (but not always) been of fairly low quality in order to make the system price competitive. Thermoplastic marking installation is also a reasonably hazardous endeavour, as hot plastic material is applied to the road under high pressure in addition to the ever present risk of “struck-by” accidents that are part of daily life in the road marking industry.

Ideally a line marking system that can provide true wet reflectivity is needed to complement the effectiveness of RRPM’s and deliver drivers consistent visual information at night, whether the road is wet or dry. By “true” wet reflectivity, we mean a system that is capable of reflecting when it is covered with a film of water of any thickness. In conjunction with a wet recovery/dry optic, this would provide a line marking that is visible at all times.

Refractive Index

So why do pavement markings disappear when it rains? Quite simply, it is due to a fundamental physical property of all glass beads, refractive index. Refractive index can be thought of as how a material bends light that passes through it. To see it in action, put a straw in a glass of water and look at the glass from the side. You will see that the straw appears to bend at the air/water interface.

In dry conditions, a glass bead with a refractive index of between 1.5 and 1.9 is able to effectively retroreflect incident light back to the driver (figure 2). When a film of water forms on the spherical bead, the lens becomes more elliptical and thus a higher refractive index is required of the bead in order to overcome the interference of the water. The optimum refractive index for wet reflectivity is between 2.4 and 2.5.

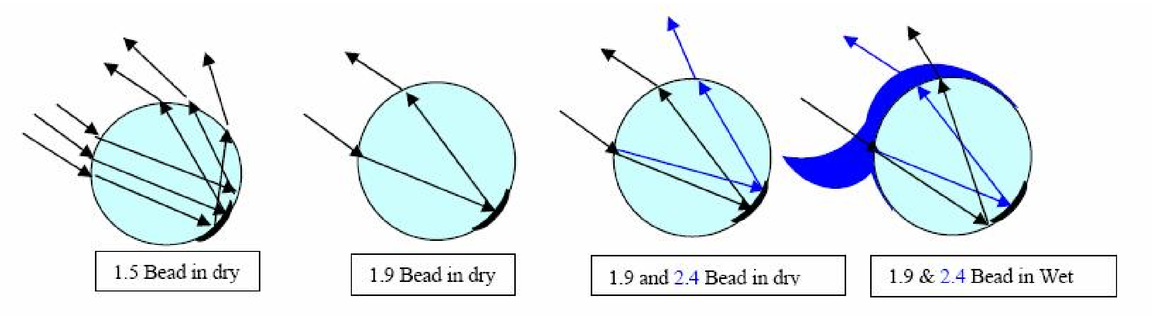


Figure 2 Path of light return vs refractive index

Achieving such high refractive index with glass beads for roadmarking is impossible. Glass becomes very soft as its refractive index increases and as such 2.4-2.5 refractive index glass beads do not possess the strength needed to survive on our roads. Clearly, an alternative material is required that can be manufactured with high refractive index without reducing the hardness of the finished product. Such a high refractive index can be achieved through the use of microcrystalline ceramic beads. Ceramic is a particularly hard material, and ceramic spheres have crush strength well in excess of 50,000 psi – making ceramic an ideal candidate material for producing a durable, high index reflective bead.

Microcrystalline Ceramic – The Key to True Wet Reflectivity

This new system is comprised of 2.4 refractive index microcrystalline ceramic beads for wet retroreflectivity, high performance glass beads for dry reflectivity and a high build waterborne paint to provide maximum durability of the line on the road. The 2.4 index microcrystalline ceramic beads are incorporated into the linemarking in the form of a sand core encrusted with many individual ceramic beads. This structure is pictured in figure 3, embedded in paint along side a glass bead and is called an “element”. Figure 4 shows a macro view of elements and beads in a linemarking.

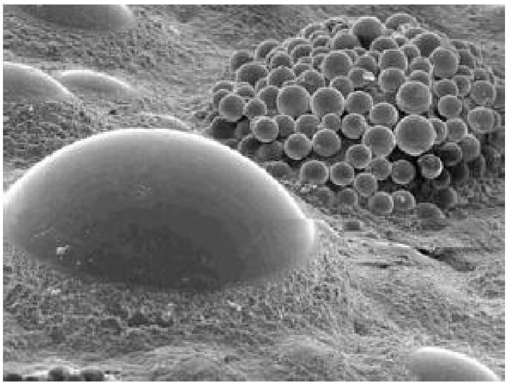


Figure 3 Glass bead and element

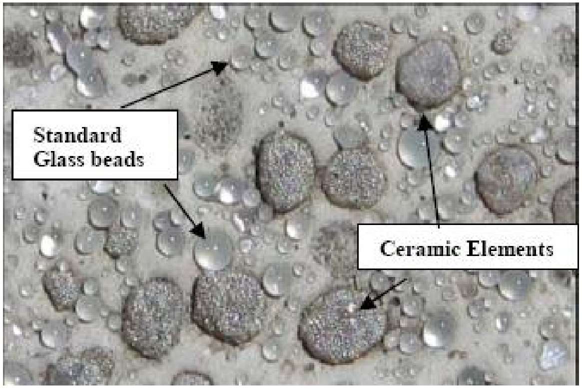


Figure 4 Macro view of elements and bead

When the linemarking is dry, the glass beads provide reflectivity as is the case in traditional linemarkings. When the linemarking is wet, the glass beads become ineffective and the elements take over as the retroreflective component of the line. As the water drains away from the linemarking and enters the phase known as wet recovery, glass beads slowly begin to reflect and work together with the still-wet elements to maximise the visibility of the line. Once the line is completely dry, the glass beads again take over as the primary reflective lens.

The elements must be matched with a high build paint that is applied at 600-700 micron thickness to ensure adequate element sink. Furthermore, the high build paint gives longer road presence to the line and improved retention of the glass beads & elements in comparison to low build waterborne paints. The high build paint must be formulated with a specific resin binder that has been matched with the elements.

High build paints are not widely used in Australia at this stage, however they are a true long life product and far outperform low build waterborne paints in terms of road presence and reflectivity over extended periods of wear.

The microcrystalline ceramic elements are manufactured by 3M, who are working in conjunction with Potters Industries as the glass bead supplier and PPG White Knight safety paints as the manufacturer of the specially formulated high build waterborne paint. Hereafter, this will be referred to as the “All Weather system”.

Application and Performance

The beauty of this new system is in its simplicity. It can be applied using conventional waterborne paint application equipment requiring only minor modification to facilitate a second drop of microcrystalline ceramic elements. Once applied, the high build paint ensures that the line marking will continue to provide effective reflectivity beyond that point at which a standard waterborne line would fail.

The combination of wet reflective elements and glass beads provides a line marking that delivers equal dry and wet recovery reflectivity values, with readings in excess of 400 mcd/lux/m^2 possible. When the line is flooded with water, or is in a “continuous wet” condition retroreflectivity of greater than 200 mcd/lux/m^2 is achievable. By comparison, a standard large glass bead pavement marking will display wet recovery values of between 1/4 to 1/2 the magnitude of the dry measurement and continuous wet measurements of below 30 mcd/lux/m^2 are normal. To put this number in perspective, it is widely held that in order for a pavement marking to be effective it must provide at least 100 mcd/lux/m^2 in retroreflectivity. In this context, “effectiveness” means the linemarking is bright enough to give the driver enough preview time to make safe driving decisions. Figure 5 shows a comparison of a traditional marking and a marking featuring the wet reflective element on the same stretch of road during rainfall.

Figure 5 Standard road marking (left) vs All Weather marking (right) during rainfall

Field Performance of this System

Linemarkings containing the microcrystalline ceramic elements are now being implemented widely around the world. Thus far Australia is the only country where the elements are strategically paired with a high performance glass bead. That decision was made locally to maximise the cost/benefit equation for this system, so specifying agencies would be provided with a high quality dry optic to complement the wet reflective element to ensure that this system represents the best waterborne marking available. Although this does have an impact on price, the performance and durability advantages outweigh the small increase a high quality bead introduces.

Due to this peculiarity, performance data from other countries don't reflect the performance seen in Australia. There are a number of locations around Australia where the wet reflective element system has been applied and a handful of these are being actively monitored by either the responsible road authority or the alliance partners.

Monaro Highway

The first and longest running example was installed by the NSW Roads and Traffic Authority, who are continuing to monitor performance of the line. A short section of the Monaro Highway in the ACT was marked with a number of linemarking treatments and application variables. After 18 months on a high traffic roadway, the optimum application case for the wet reflective elements is still returning wet recovery values of just under 200 mcd/lux/m^2. This particular marking used drop-on beads as the dry optic, so the contribution of glass beads to the wet recovery is expected to be less than 50 mcd/lux/m^2. Correctly applied in conjunction with a good wet recovery bead, such as Potter's Visimax™ (or even Visibead™), wet recovery in excess of 300 mcd/lux/m^2 would not be an unreasonable expectation after this time period. Figure 6 shows the wet and dry performance of two of the better applications from the this RTA trial.

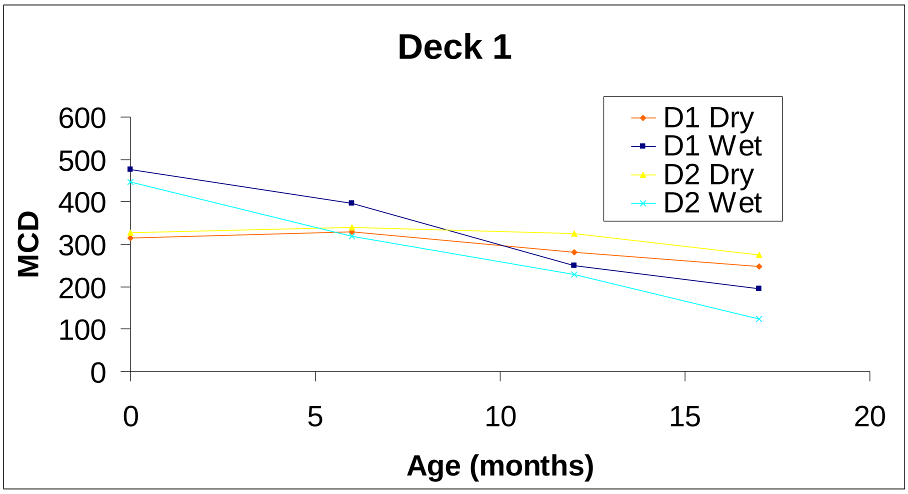


Figure 6 Results of ongoing NSW RTA trial of All Weather system

Each of the two markings in the above trial used drop-on beads as the dry optic. As a result, the wet measures can be considered to be almost solely due to the performance of the wet reflective element.

An unexpected performance enhancement caused by the elements was the impact they had on skid resistance. In this trial, D1 and D2 from the above figure possessed BPN skid resistance values of 66 and 62 units respectively. In comparison, trialling of quartz and crushed glass skid treatments in this trial returned only 45 and 50 BPN skid resistance values. Based on this data, line markings featuring the wet element may not require additional anti-skid additives to meet the 45 BPN requirement for linemarkings.

Mona Vale Rd

A section of Mona Vale rd in Sydney has recently been painted with this system. Here two edge lines were marked in the All Weather system of 3M elements, Potters Visimax and PPG Hi-Dura paint while the centreline was marked using an RTA141 compliant thermoplastic marking. After 4 weeks of trafficking, the edge lines posses an average dry R_A of 440 mcd/lux/m^2 and 60 second wet recovery of 300 mcd/lux/m^2.

The thermoplastic centreline was applied during the same week and was measured on the same day the above measures were obtained. For the thermoplastic marking, dry R_A averaged 225mcd/lux/m^2 and wet recovery readings averaged 72 mcd/lux/m^2.

These results on a 4 week old thermoplastic marking are particularly concerning, as the linemarking would already be below the forthcoming NSW RTA145 performance based specification for pavement markings. The new specification dictates *minimum* 60 second wet recovery reading of 75 mcd/lux/m^2. This particular marking had not yet lost a significant amount of the surface applied optics so could be considered a “best case” reading for the thermoplastic marking. Further, at 225 mcd/lux/m^2 dry, some might feel this is uncomfortably close to the RTA145 intervention level of 150 mcd/lux/m^2 dry retro value.

M5 South West Motorway Sydney

Another major application of this system has been on the M5 South West Motorway in Sydney. A section of road between Liverpool and the Crossroads was recently marked and has been measured after 4 weeks of trafficking. In this case, the left edge line and lane line were marked as All Weather lines and the right edge line was marked to the RTA 141 waterborne paint specification. This particular length of road has traffic of approximately 110,000 ADT including a large number of heavy vehicles so is providing a good demonstration of the durability of the microcrystalline ceramic elements.

The left hand edge line returned an average dry retro of 395 mcd/lux/m^2 and 60 second wet recovery was 280 mcd/lux/m^2. The RTA141 right edge line has dry results of 270 mcd/lux/m^2 and wet recovery of 120 mcd/lux/m^2. A crude flood measurement was also made where the lines were flooded with 1L of water and measured with 3-5 seconds recovery time. The all weather line read, on average, 160 mcd/lux/m^2 while the RTA141 line returned 25 mcd/lux/m^2.

Wet weather inspections of this site have confirmed that the all weather system is effective in natural rainfall events. The road owner, Interlink Roads, has reported that a customer has actually phoned their control tower after a particularly heavy shower and asked why they didn't remark the whole road – the driver's perception was that the brand new RTA141 line was an old line when viewed in wet weather alongside the All Weather linemarkings.

AS4049.4 & RTA145 – Towards Performance Based Linemarkings

AS4049.4 –High Performance Pavement Marking Materials and the forthcoming RTA145 specification are two instruments that represent a revolution in how linemarkings are qualified and the expectations specifiers have regarding performance. Hand in hand with these is the assumption that more expensive initial applications will become the norm provided they deliver value for money over the life of the marking. This value can be represented in terms of longer life or alternatively, performance characteristics that are not currently provided (for example, wet reflectivity).

In the context of the RTA145 specification, this system would be expected to deliver pavement markings that exceed the requirements of the specification for timeframes in excess of 2 years. The wet recovery requirement of RTA145 of 75mcd/lux/m^2 should not be viewed as the "safe" level of performance for a linemarking. Rather it is the minimum acceptable performance level. As was stated previously in this paper, the safe minimum retro in any condition is considered to be approximately 100 mcd/lux/m^2. However, this value probably understates the truth. Research has indicated that values as high as 200 mcd/lux/m^2 are required to provide adequate preview time for drivers at speeds of up to 90 km/h[1]. This should be of particular interest to operators and highways, tollways and rural roads where speeds in excess of 80km/h are common.

According to AS4049.4, the All Weather system would be considered an RD2-3 and RW2-3 pavement marking. Careful application and selection of dry optics will give RD3 and RW3 performance levels, while the elements have been shown to provide slip ratings of SL3 (>54 BPN).

Conclusion

This system represents a major step forward in pavement marking and finally provides road owners with a means to greatly enhance the safety and performance of their pavement markings for the times when road users need it most. Furthermore, it complements the current AS4049.4 requirements for the highest performance classes and provides a system compliant with the upcoming RTA145 specification. However, this pavement marking actually delivers performance in a line that no other system can – true wet reflectivity. Wider implementation of the microcrystalline ceramic element technology can be expected to provide measurable improvement to road safety outcomes by improving driving conditions during the most hazardous and challenging periods.

Future work with this material involves expanding the application of the element technology into other pavement marking systems such as thermoplastic and two-part cold applied, for now though, the focus remains heavily on high build paint as the carrier because it is believed this provides the best price/performance profile.

DRIVER FOCUSSED DESIGN OF RETROREFLECTIVE SHEETING

Retroreflective sheeting is the material which forms the basis of the sign face, making the sign visible during hours of reduced light. The retroreflectivity of the material is a major determinant of the brightness, or observed luminance of the sign. There are a number of methods for quantifying retroreflectivity but in general the higher the retroreflectivity, the higher the luminance. Together with factors such as sign placement, legend design, font and message, sign luminance makes the sign legible to the driver.

Sign sheetings from the major global suppliers have trended towards microprismatic materials. Microprismatic reflective materials consist of microscopic air-filled, resin prisms that have been impressed into the internal structure of the sheeting with precision tooling. These prisms then reflect incident light by a process known as “total internal reflection”, where the light enters the prism and reflects off multiple faces of the prism and is then returned to the light source. In a roadway scene, this light source is the approaching vehicle. When headlights are retroreflected by a sign face, the light is returned to the driver in a cone shaped distribution. This is known as the divergence cone or cone of retroreflection. By modifying the microprismatic geometry during manufacture of the sheeting, this divergence cone can be altered such that the light can be preferentially distributed to areas in the cone where it is most likely to be useful to the driver or application. Herein lies the great advantage of prismatic retroreflective sheetings over traditional glass bead based materials (Engineer and High Intensity grades).

Road authorities and traffic engineers have very little control over many of the factors which impact of sign luminance. Increasing numbers of imported vehicles are driving a trend towards VOA and HID headlights which deliver less light into the areas where traffic signs are usually positioned, meaning that signage needs to posses higher retroreflectivity to maintain luminance at useful levels. Australia’s aging population has been well documented[2] as has the link between age and reduced visual acuity. Providing higher sign luminance can be expected to improve the legibility and usefulness of road signage to these older drivers. While most of the factors that lead to reduce signage effectiveness are out of the control of road authorities, they do have the ability to select which materials will be used to construct road signage. Selecting higher performance sheeting as the base material for signage will result in signs that are of more benefit to the greatest percentage of road users.

Australia is also experiencing strong growth in road freight volumes, with growth of approximately 5.8% per annum for the past 25 years.[3] The bulk of this growth has been in increased kilometres driven by articulated trucks. Furthermore, until recently sales of four wheel drive large vehicle were steadily increasing. While sales of these vehicles are currently declining, they still make up over 20% of new vehicles sold in Australia. These larger vehicles have a greater displacement between the driver and the headlights, which increases the observation angle between the headlight, a sign and the driver. In other words, this puts the driver’s eye further from the centre of the previously mentioned cone of retroreflectivity. As observation angle increases, sign luminance typically decreases. Figure 7 contains a pictorial depiction of observation angle in the simplified case of a motorcycle (one headlight).

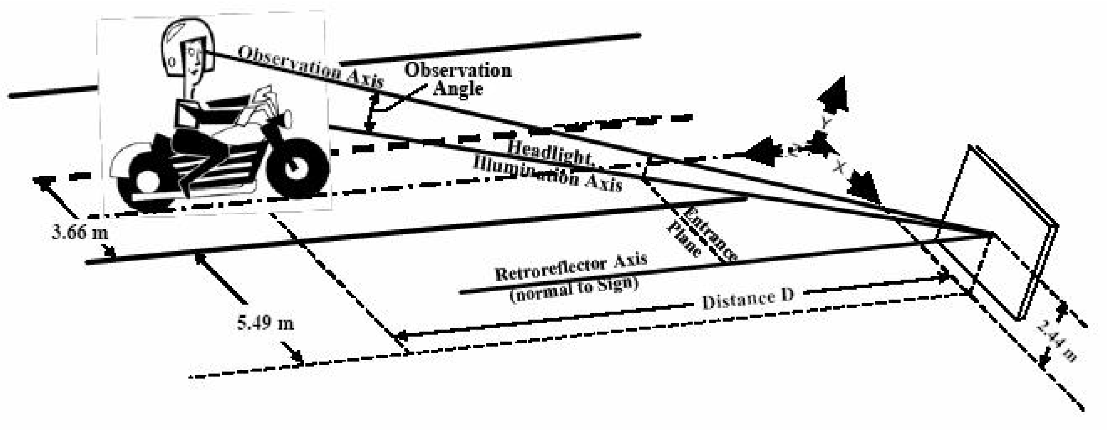


Figure 7 – Observation angle

Clearly, for signage to be effective it must be constructed from sheeting that provides useful levels of retroreflectivity over the range of observation angles encountered in typical driving scenarios. This means the sheeting must serve the narrow observation angles present for most car drivers through to the much wider observation angles experience by truck drivers and everything in between.

Yet another factor effecting sign luminance is the entrance angle, or the orientation of the sign relative to the approaching vehicle. Observation angle is relatively independent of entrance angle and sign placement. Wider entrance angles are present for overhead and right hand mounted signage and performance at these wider entrance angles is important for sign visibility but a focus on observation angle is relevant to virtually every roadway situation. Maintaining entrance angles below 15° is usually achievable through good traffic engineering, but observation angle is a critical variable that can not be controlled by the traffic engineer. It is dictated by the vehicle type.

One factor that does effect observation angle is the distance between the vehicle and sign. As the vehicle approaches the sign the observation angle steadily increases. Because observation angle varies with distance, we first must understand the distances at which a driver acquires information from a sign before making any decisions about the important observation angles a sign must perform at.

Sign Information Acquisition Distances

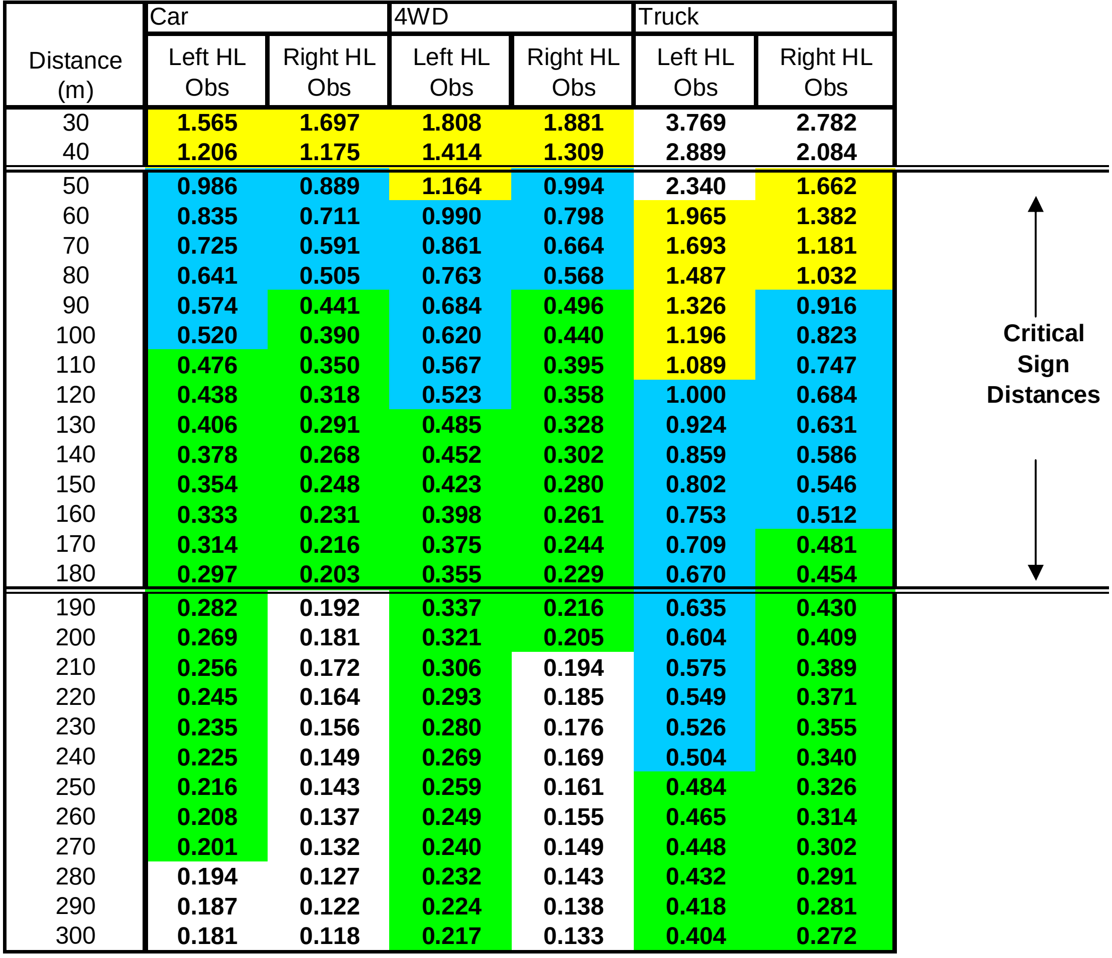
There have been a number of studies directed at determining when a driver reads, comprehends and acts on the information presented on a sign[4-7]. At present, there is no general consensus on the actual visual acquisition model which best describes the driving task. It is more likely that different models are valid in different driving circumstances. For instance, the attentional load on the driver in urban areas is quite different from that in rural scenes. This may lead to drivers using different techniques to perform their visual search task and therefore place different demands on sign legend and luminance.

Irrespective of the visual model used or description of the sign reading task, the majority of studies reach the conclusion that the key distances for all aspects of sign comprehension are between 50 and 160 metres from the sign. A vehicle travelling at 60km/h will cover this distance in approximately 7 seconds and the driver will look at the sign multiple times during this period while comprehending the sign message. This distance range covers both urban and rural environments. Next, we will look at the observation angles that occur during this distance range from the sign.

Observation Angles for Critical Sign Distances

As previously discussed, observation angle is dependant on the vehicle type and the distance of the vehicle from the sign. Table 1 was generated using the Ergo 2001 Exact Road Geometry Output[8] software tool. The vehicles used were the included CEN car, a custom 4 wheel drive and the CEN truck.

Table 1 Observation angle (deg) as a function of distance from sign



Distance (m)	Car		4WD		Truck	
	Left HL Obs	Right HL Obs	Left HL Obs	Right HL Obs	Left HL Obs	Right HL Obs
30	1.565	1.697	1.808	1.881	3.769	2.782
40	1.206	1.175	1.414	1.309	2.889	2.084
50	0.986	0.889	1.164	0.994	2.340	1.662
60	0.835	0.711	0.990	0.798	1.965	1.382
70	0.725	0.591	0.861	0.664	1.693	1.181
80	0.641	0.505	0.763	0.568	1.487	1.032
90	0.574	0.441	0.684	0.496	1.326	0.916
100	0.520	0.390	0.620	0.440	1.196	0.823
110	0.476	0.350	0.567	0.395	1.089	0.747
120	0.438	0.318	0.523	0.358	1.000	0.684
130	0.406	0.291	0.485	0.328	0.924	0.631
140	0.378	0.268	0.452	0.302	0.859	0.586
150	0.354	0.248	0.423	0.280	0.802	0.546
160	0.333	0.231	0.398	0.261	0.753	0.512
170	0.314	0.216	0.375	0.244	0.709	0.481
180	0.297	0.203	0.355	0.229	0.670	0.454
190	0.282	0.192	0.337	0.216	0.635	0.430
200	0.269	0.181	0.321	0.205	0.604	0.409
210	0.256	0.172	0.306	0.194	0.575	0.389
220	0.245	0.164	0.293	0.185	0.549	0.371
230	0.235	0.156	0.280	0.176	0.526	0.355
240	0.225	0.149	0.269	0.169	0.504	0.340
250	0.216	0.143	0.259	0.161	0.484	0.326
260	0.208	0.137	0.249	0.155	0.465	0.314
270	0.201	0.132	0.240	0.149	0.448	0.302
280	0.194	0.127	0.232	0.143	0.432	0.291
290	0.187	0.122	0.224	0.138	0.418	0.281
300	0.181	0.118	0.217	0.133	0.404	0.272

Critical Sign Distances

The cells in table 1 have been formatted to be green, blue and yellow for observation angle ranges of 0.2º-0.5º, 0.5º-1.0º and 1.0º-2.0º, respectively. The distances at which the driver is actively using the sign as previously discussed is shown and labelled "critical sign distances".

We can see the huge impact that vehicle type has on observation angle in the critical sign distance range. As expected, cars have the smaller observation angles of the three vehicle types followed by the 4 wheel drive and the truck but for all vehicles the range of 0.5º-1.0º is significant. The car has observation angles in the range that is typically of where most reflective sheetings display their best performance, however closer to the 50m mark observation angle is approaching 1.0º. Interestingly, the truck has very high observation angles above 1.0º as far away at 100m from the sign, which is within the range of where most researchers have demonstrated drivers are actively using signage.

By examining this table, we can make decisions on exactly which observation angles are the most important when designing or selecting a reflective sheeting to meet the needs of the widest range of drivers. Looking at observation angle in this way demonstrates how important controlling divergence is when designing prismatic sheeting. Control of divergence allows us to direct the reflected light to the observation angles that will provide sufficient luminance in the 50-180m sign distance range.

Sending an adequate amount of light to such a wide range of observation angles is a challenging design objective. When directing this light it is a case of “robbing Peter to pay Paul”, as there is only a limited amount of reflected light available to be distributed. This is where the efficiency of the reflective sheeting becomes important.

Retroreflective Efficiency

The efficiency of a reflective sheeting can be thought of as the total light return of the material. A 100% efficient retroreflector would return all of the incident light from a vehicles headlights in the divergence cone, while a 0% efficient material would return none. In reality, 100% efficient retroreflectors do not exist. This is because of physical losses due to specular, or mirror reflection from the surface (seen as headlight glare) and tiny imperfections in the material. Furthermore, specific optics systems are limited in their efficiency by the nature of their construction. For example, only 28% of the surface of a glass bead is actually retroreflective. Figure 8 shows a 2-dimensional view of a glass bead and the retroreflective area is depicted in white. This is actually a physical property of glass beads caused by a combination of the bead’s shape and refractive index.

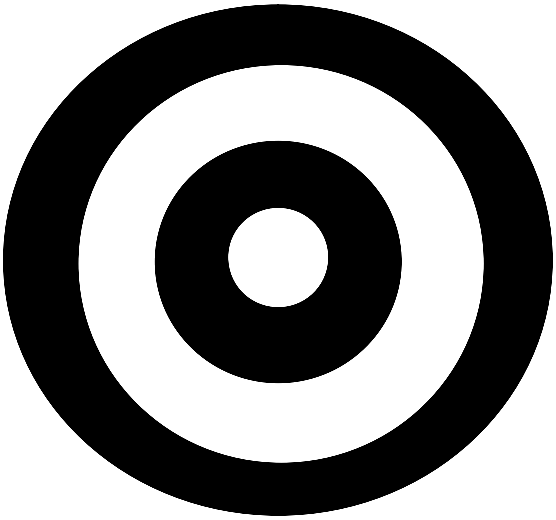


Figure 8 – Reflective surface of a glass bead

Likewise for most prismatic materials, there are physical limitations to their efficiency. Traditional microprismatic construction has been based on using triangular prisms (cube corners) as the reflective optic. However only 67% of the cube corner behaves retroreflectively. This is because light that enters the corners of the prisms only reflects off two of the three faces. For retroreflection to occur the light must hit all three faces, so light entering the corners is therefore lost. Figure 9 shows an array of triangular prisms and the retoreflective area is highlighted in blue. The white areas represent the corners, where light entering the prism is not retroreflected.

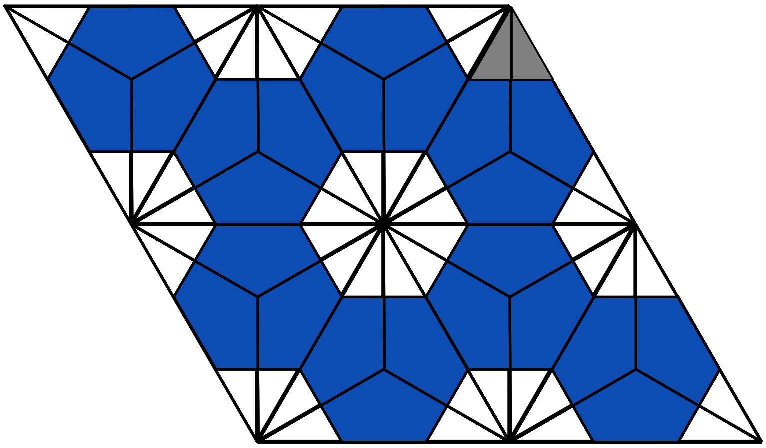


Figure 9 Retroreflective area of cube corner prismatic sheeting

In the case of cube corner reflective sheetings, 67% represents the *theoretical* efficiency of the sheeting. Once the physical losses such as imperfections and mirror reflection are accounted for, the actual efficiency of these materials drops to approximately 30%. That is, 30% of the light that hits the sign is available to be returned to the driver in the cone of retroreflectivity.

Figure 10 shows the actual retroreflective efficiency of a number of common reflective materials.

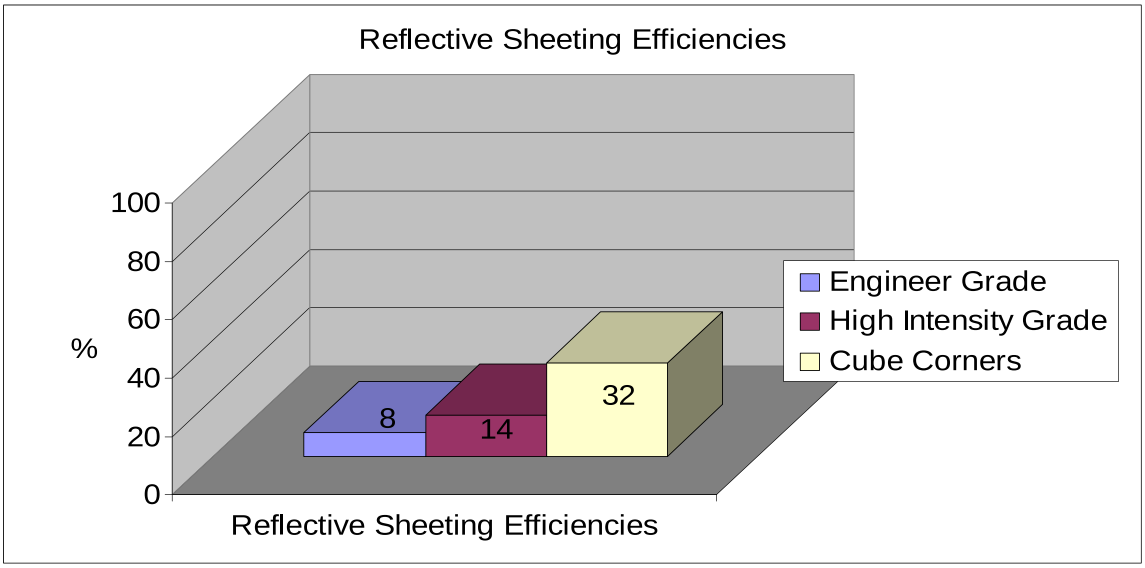


Figure 10 – Percentage of light returned by reflective sheeting types

While it is possible to deliver light to the observation angles discussed above with cube corner microprismatics, doing so requires that light be removed from some other area of the divergence cone. This means that relative to each another, different cube corner microprismatics are designed to sacrifice reflectivity in one area (such as long distance viewing) to compensate for another area (such as short approach, wide angle viewing), as they all have similar amounts of light to distribute.

The only means to escape from this constant trade off is to find a way to increase the retroreflective efficiency of microprismatic sheeting. In other words, manufacture a sheeting that returns more of the available light to the driver.

Micro Full Cube Sheeting

This has been achieved by designing a prism geometry called micro full cube, or simply full cube. A full cube reflective sheeting design takes the reflective area of the cube corner design and discards the ineffective corners. Then, the reflective centres are replicated side by side to create a fully retroreflective surface. Figure 11 shows this progression.

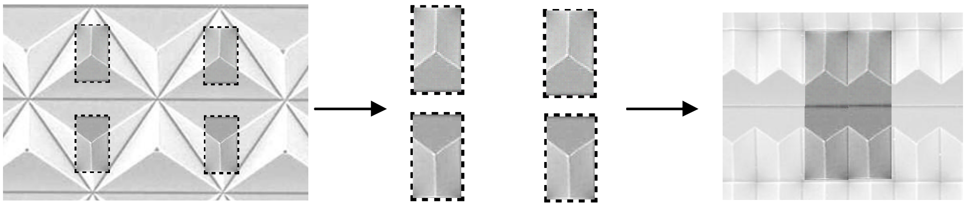


Figure 11 From cube corner to full cube

Figure 11 shows the dramatically different microscopic appearance of traditional cube corner microprismatics on the left alongside the micro full cube design on the right. When viewed in this fashion it appears a trivial development but in reality it is far from that.

With the full cube prismatic design, the actual efficiency of the material is 58% once physical losses have been accounted for. That means 58% of the light which strikes the sign face is retroreflected to the driver in the cone of retroreflection. By carefully controlling the divergence, the light can be distributed without becoming blinding to any driver. In other words, retroreflectivity at narrow observation angles can be kept relatively equal to that of incumbent high performance sheetings while retroreflectivity at wider observation angles is increased.

How Prismatic Sheetings Direct Light

The traditional explanation for how cube corner sheetings reflect light is depicted in figure 12. This is a simplification of the process at play.

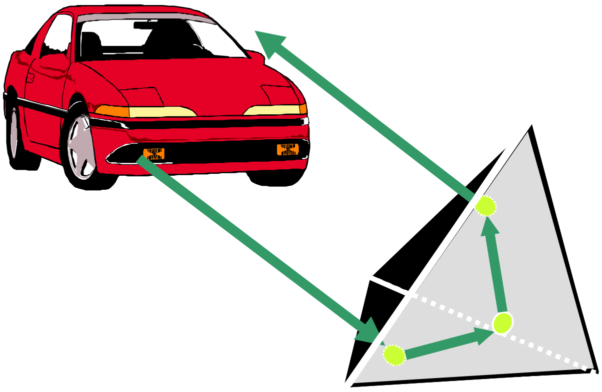


Figure 12 – Total internal reflection.

In reality, a perfect triangular prism as pictured here would reflect the light directly back along its incident axis. That is, it would be reflected straight back to the headlights of the vehicle! Obviously this is all but useless for a road sign, as no light would reach the driver. In reality, the light is directed to where the designers want it to be by very small variations in the angles of the three sides of the prisms. These variations in angles are called “dihedral errors”. By introducing small dihedral errors the way a prism reflects light is dramatically altered. Figure 13 shows two spot diagrams depicting where the light directed with minor changes in prism geometry.

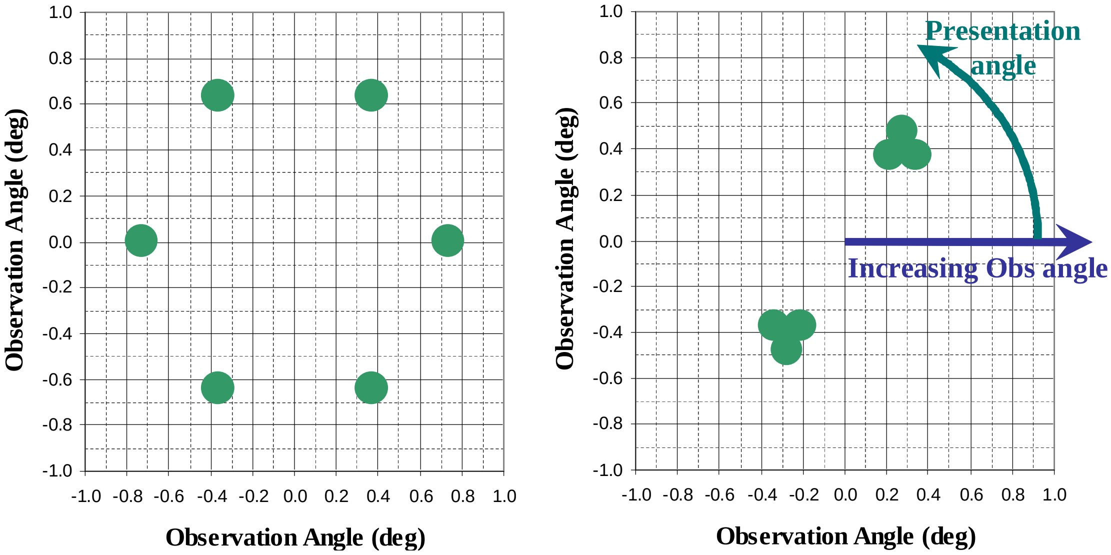


Figure 13 Spot diagrams for two different prism geometries.

In figure 13, we are viewing the cone of retroreflection along its axis. On the left hand graph, the light beam entering the prism is split and directed to the 6 observation angle pairs indicated. Each point can be thought of the lateral observation angle vs the vertical observation angle. The graph on the right is derived from a prism geometry that is only slightly different but as we can see the light is concentrated in two regions of the cone. All other areas of these graphs receive no light, so a sign manufactured from a sheeting with either of these profiles would have large dark areas where no luminance is available.

Clearly, a prismatic sheeting that is designed for traffic signage needs a number of different prism geometries to be present in the film. These differing prisms then work together to distribute light widely enough for the sign to be visible. Figure 14 shows a fairly typical example of the complexity required by the design of modern retroreflective sheeting. For more detail on this particular example, see the reference[9]. Each different coloured shape on this plot indicates the points in the divergence cone that a particular prism geometry is directing light to. We can see that the distribution of light is very broad, and this is necessary for the material to be a functional sign sheeting. This example has around 80 unique prisms each replicated on the surface of the material in a repeating pattern. It is through this designed replication of pre-engineered differences that all prismatic sign sheetings are manufactured. The cubes are individually designed to provide the final reflectivity profile that is desired. Based on the large amount of light that is concentrated at wide observation angles, we might assume that this example would conform to Class 1W according to AS/NZS1906.1.

When the distribution of light is considered in this deliberate way, it becomes apparent that increasing the efficiency of the sign sheeting is of inherent value. A higher efficiency sign sheeting would allow us to distribute that available light more evenly throughout the cone to ensure there are no dark spots and also to produce signage that approaches equal luminance to the drivers all vehicle types.

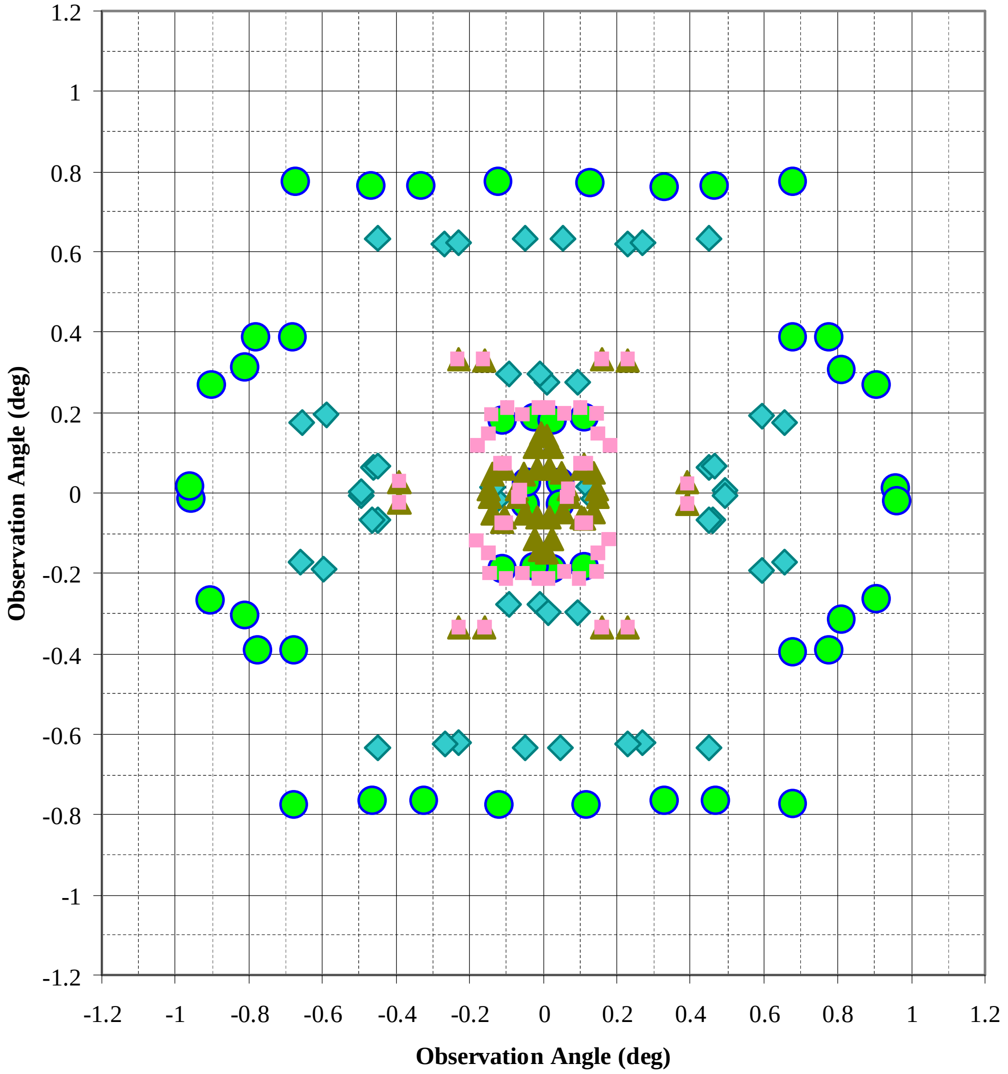


Figure 14 Spot return of a typical prismatic material

Defining Retroreflective Performance

Traditionally, the retroreflective performance profile of a material has been defined through the coefficients of retroreflection at certain observation and entrance angle combinations as described in various global standards. However, it is difficult to strictly define the actual performance of a material in this manner. One way to do so is to consider the fractional retroreflectance (R_T) of a material. R_T is described in detail in ASTM E808-01[10] but simply, it is the sum of all incident light that is retroreflected through a defined observation angle range. When measured over a wide enough observation angle range it equates to the total light return of the sheeting. R_T is mathematically represented as a complex integral:

$$R_T = \int_{\alpha=0}^{\alpha_{\max}} \int_{\gamma=-\pi}^{\pi} \left(\frac{R_a}{\cos(\beta)}\right)(\alpha)\, d\gamma \quad d\alpha$$

here α is the observation angle, γ is the presentation angle, β is the entrance angle and R_a the coefficient of retroreflection. The output of this equation is the amount of light returned by the material in the cone of light from the centre out to the observation angle $\alpha_{\max}$. Practically, this is measured by taking a series of R_a measurements in a fine grid of observation and presentation angles. By plotting the sum of the presentation angle results for each observation angle we obtain a curve showing the efficiency of the sheeting. Figure 15 shows the R_T plots for a few common reflective material types.

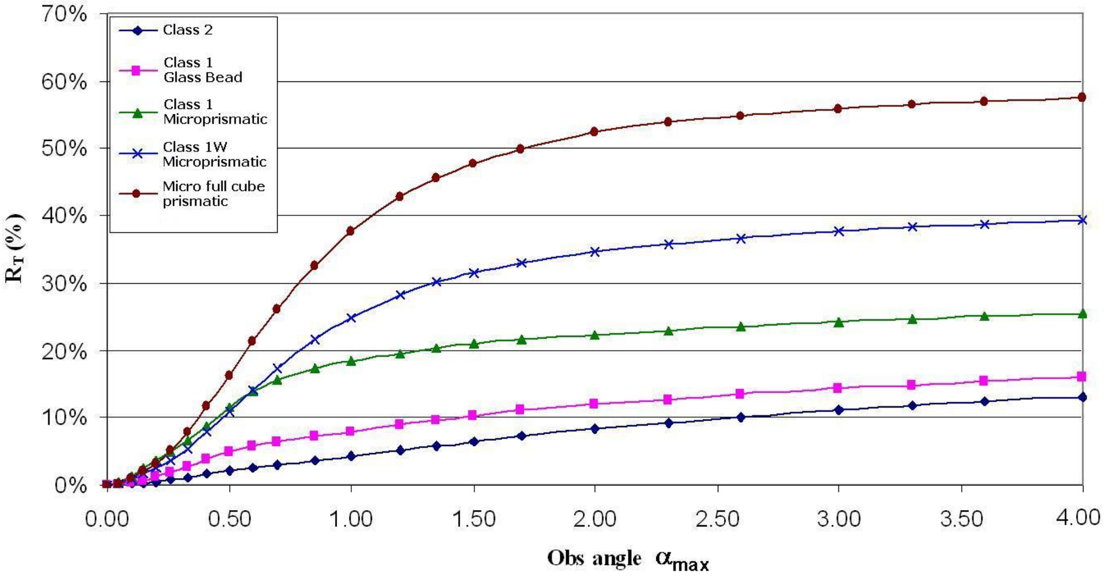


Figure 15 – R_T vs Observation angle for several sign sheeting classes

From this figure we can see the order of sheeting efficiency that has been previously discussed, with the two glass bead based materials having the lowest overall light return then the prismatic class 1, prismatic class 1W and micro full cube material returning the most overall light. This graph also tells us where each of these particular materials direct the most light. The gradient of each curve at a particular observation angle is equal to the amount of light focussed at that observation angle. Taking this gradient data out and viewing it plotted against observation angle will give a more familiar graph shape, figure 16.

Figure 16 clearly shows where each sheeting type distributes light. For the micro full cube sheeting, the design decision was made to place most light in the previously established driver critical observation angle window from 0.2 to 1.5.

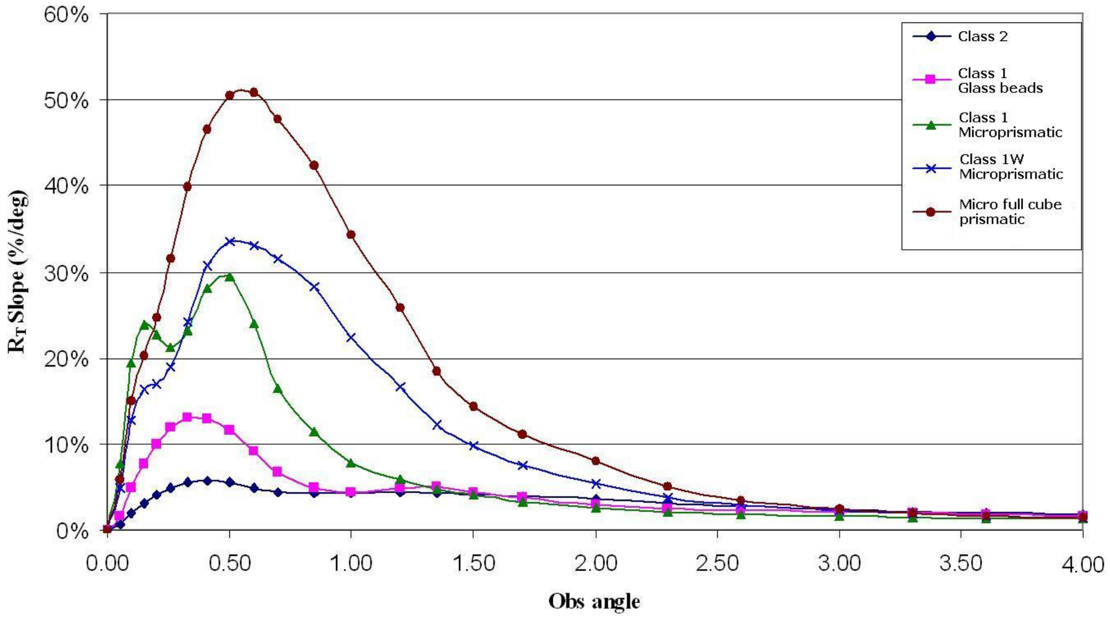


Figure 16 – R_T Gradient vs Observation Angle or “Where the light is going”

Providing this amount of light to such a wide observation angle range is only made possible by increasing the efficiency of the material. In short, a micro full cube design allows for a prismatic material to be manufactured that provides enough long distance (narrow observation angle) luminance to been seen early and then enough wider observation angle luminance to allow the driver to read the message as they approach the sign.

Conclusions

For road signage to be as effective as possible, it is important that all road users are considered during the material design and specification stages. It has been established that in the critical sign reading distances, the important observation angles all drivers of all vehicles experience to some degree are between 0.5-1.5º. With this in mind, signage materials should be specified to deliver the bulk of their retroreflectivity within this range.

Micro full cube sheeting has been shown to deliver the most amount of light to drivers at most observation angles and is superior to cube corner materials in the driver critical observation angle region.

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