Innovations Deserving
Exploratory Analysis Programs

NCHRP IDEA Program

A Retroreflective Road Lane Marking Tape 1,000X Brighter than Existing Technology

Final Report for
NCHRP IDEA Project 228

Prepared by:
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TRB TRANSPORTATION RESEARCH BOARD
The National Academies of
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Innovations Deserving Exploratory Analysis (IDEA) Programs Managed by the Transportation Research Board

This IDEA project was funded by the NCHRP IDEA Program.

The TRB currently manages the following three IDEA programs:

- The NCHRP IDEA Program, which focuses on advances in the design, construction, and maintenance of highway systems, is funded by American Association of State Highway and Transportation Officials (AASHTO) as part of the National Cooperative Highway Research Program (NCHRP).
- The Safety IDEA Program currently focuses on innovative approaches for improving railroad safety or performance. The program is currently funded by the Federal Railroad Administration (FRA). The program was previously jointly funded by the Federal Motor Carrier Safety Administration (FMCSA) and the FRA.
- The Transit IDEA Program, which supports development and testing of innovative concepts and methods for advancing transit practice, is funded by the Federal Transit Administration (FTA) as part of the Transit Cooperative Research Program (TCRP).

Management of the three IDEA programs is coordinated to promote the development and testing of innovative concepts, methods, and technologies.

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IDEA Programs
Transportation Research Board
500 Fifth Street, NW
Washington, DC 20001

"A Retroreflective Road Lane Marking Tape 1,000X Brighter than Existing Technology"

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Prepared for the IDEA Program Transportation Research Board

The National Academies

by

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We thank the National Academies, the TRB Highway IDEA program, and our expert team of reviewers for providing funding and guidance during the Phase I program which allowed us to verify the unprecedented performance potential of our new traffic stripe.

We thank our team for enabling us to make and successfully test the first fully functional prototypes of the new traffic stripe, including:

- 10X Technologies for making the first TPU and cast PU parts
- Film Optics (U.K.) for making the diamond-turned molding tools for additional parts
- Lubrizol Advanced Materials for guidance on their TPU materials and for providing compression-molded TPU parts for our prototype traffic stripes
- Road Vista/Gamma Scientific for performing certified retroreflectivity testing of multiple prototypes in their laboratory according to ASTM Standards D4061, E809, and E1710, and CEN Standard EN1436, and for providing advice on future testing of installed ultra-bright stripes
- Dr. Paul Carlson, an internationally recognized expert on traffic safety, for providing invaluable advice about the new traffic stripe technology, and for coordinating the installation of prototypes by TRP Infrastructure Services (https://trpinfrastructure.com), our newest team member

Table of Contents

EXECUTIVE SUMMARY

The innovation is an ultra-bright traffic stripe made from a thin transparent polymer film with prismatic patterns formed on both the top and bottom surfaces of the polymer film (*1 - 4*). The new traffic stripe uses neither paint nor glass beads to provide unprecedented retroreflectivity on dark highways at night.

Fig. 1 shows how the new traffic stripe works. This view is from the side of the traffic stripe showing the cross-section of the prismatic polymer film. The top surface includes light-turning prisms facing in both directions of traffic. Rays from distant headlights are totally internally reflected (TIR) by a sloped surface downward onto cube corner prisms covering the bottom surface of the polymer film. The cube corner prisms retroreflect the rays in the opposite direction so these rays eventually return to the driver (and the sensors) of the vehicle. The cube corner prism technology has been successfully used for decades in traffic signs which are very bright and durable. The present innovation enables this previously developed cube corner sign technology to be applied to traffic stripes to make the new stripes as bright as road signs, rather than 1,000 times less bright as for conventional traffic stripes with glass beads embedded in white paint.

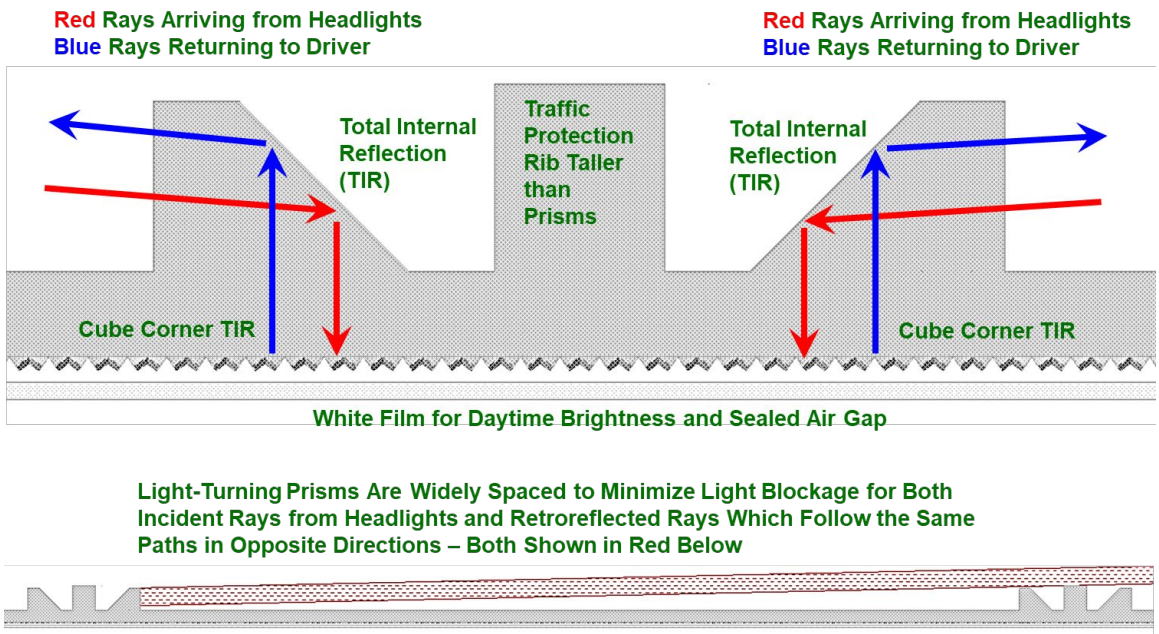

FIGURE 1 How the New Traffic Stripe Works

Fig. 1 also shows that the light-turning prisms are widely spaced apart along the traffic stripe to minimize light ray blockage for both incident and retroreflected rays. Fig. 1 also shows how taller traffic protection ribs can be added to contact vehicle tires before the light-turning prisms, thereby mitigating traffic damage.

Fig. 2 shows the preferred manner of installing the new traffic stripe in a pavement groove for further mitigation of traffic damage. The groove is cut into the highway to a depth of 3-6 mm (0.12-0.25 inch). An adhesive is used to bond the traffic stripe to the bottom of the groove. Different types of adhesives may be used, including pressure sensitive adhesives (PSAs), mixed epoxy adhesives, butyl tapes, and mastics. The depth of the groove should be greater than the combined thickness of the traffic stripe and adhesive.

The primary objective of the TRB IDEA program was to build and test the first fully functional prototypes of the new traffic stripe to prove that this new technology offered retroreflectivity values hundreds of times higher than conventional traffic stripes. This objective has been fully met.

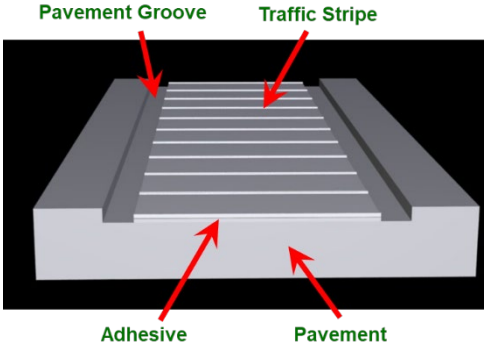

FIGURE 2 Preferred Installation Method

Fig. 3 shows certified retroreflectivity measurements for the first four prototypes made and tested under this TRB IDEA program (*5 and 6*). For comparison, Fig. 3 also includes the proposed U.S. (*7*) and European (*8*) retroreflectivity standards for high-speed roadways. Also, for comparison, an optimistic estimate of the highest known value of retroreflectivity for any previous traffic stripe is shown in Fig. 3. Note that the prototypes of the new traffic stripe are two orders of magnitude brighter than the proposed standards, and many times higher than for any previous traffic stripe. In summary, the new traffic stripe offers unprecedented retroreflectivity, as predicted.

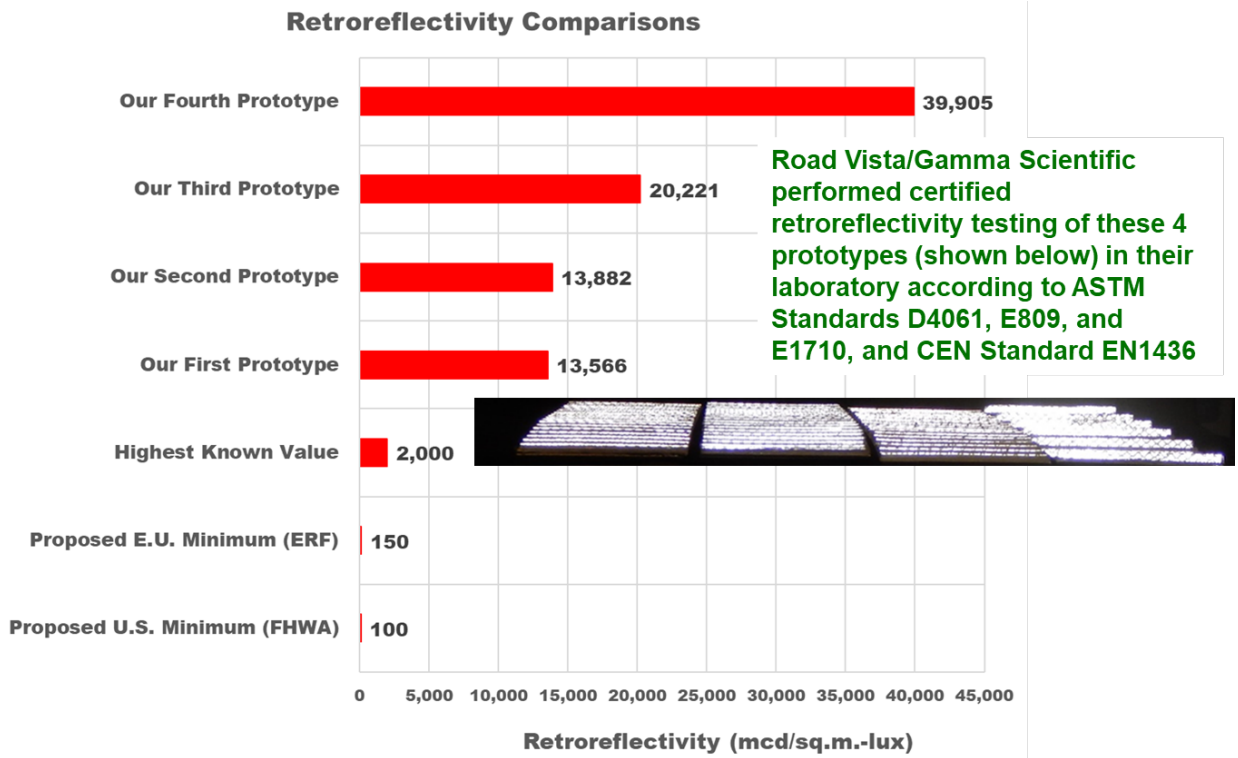

FIGURE 3 Certified Retroreflectivity Measurements of Prototypes of New Traffic Stripe

Our team has also investigated potential improvements to the basic concept of the new ultra-bright traffic stripe to increase its brightness under both dry and wet weather conditions, to make it cost-effective when mass produced, and to make it more robust to tolerate traffic damage with acceptable lifetime and durability. We have developed a roadmap to implement these improvements and to commercialize the new traffic stripe technology in the future.

We have also performed benefit/cost analyses for the new traffic stripe in terms of the value of human lives saved due to crash reduction factors for brighter stripes, and found that the new traffic stripe has a rapid payback time of only a few months.

While the prototypes fabricated to date are relatively crude and do not include the robust configuration of future commercial versions of the new traffic stripe, we have placed two small test articles on two highways, one in North Carolina and the other in Texas. Fig. 4 shows the prototype installed in a groove on I-77 in North Carolina near the Virginia border.

Our team looks forward to the near-term commercialization of this exciting new traffic stripe technology, which offers the potential of saving many lives for both human-driven and connected and autonomous vehicles (CAVs).

FIGURE 4 Prototype on I-77 in NC

IDEA PRODUCT

The product first successfully demonstrated under this TRB IDEA program is an ultra-bright traffic stripe which is hundreds of times brighter than conventional traffic stripes which still use the century-old technology of white paint with embedded glass beads. The new product uses a transparent polymer film with prismatic patterns formed into the top and bottom surfaces to accept light from approaching headlights and to efficiently retroreflect this light back to the driver and sensors of the vehicle with unprecedented retroreflectivity. No paint and no glass beads are needed for this innovative product. Two U.S. patents have already issued (*1, 2*) for the new product with more pending (*3, 4*).

The ultra-bright retroreflectivity of the new product will save lives and correspondingly offer a very short payback period and a very substantial benefit/cost ratio over its useful lifetime. Table 1 presents an example of the payback time calculation for an application as an edge line on interstate highways. In 2020, there were 5,129 deaths on interstate highways according to the NHTSA (*9*). Half of such fatalities typically occur at nighttime according to the National Safety Council (*10*). Half of all fatalities are typically due to highway departure accidents according to the FHWA (*11*). Thus, approximately1,282 fatalities on U.S. interstate highways in 2020 were due to nighttime road departure accidents. There are about 227,000 miles of U.S. interstate highways according to the USDOT (*12*). Therefore, there were approximately 0.0056 deaths per lane mile due to nighttime road departure accidents on interstate highways in 2020. The comprehensive cost of each fatality was approximately $10.7 million according to USDOT guidance (*13*). Combining the previous values leads to the remarkable cost of nighttime roadway departure deaths on American interstate highways of over $60,000 per mile. If we assume that the baseline brightness of edge lines is equal to the proposed FHWA standard 100 mcd/sq.m.-lux (*7*) and we replace such conventional edge lines with our new ultra-bright traffic stripe, we can estimate the reduction in crashes and deaths using published Crash Reduction Factor (CRF) equations for brighter edge lines on high-speed roadways, specifically, CRF 2116 (*14*). Our new traffic stripe prototypes have been measured at a typical initial retroreflectivity of about 29,000 mcd/sq.m.-lux (*15*). If we very conservatively assume a 99% degradation of this initial brightness due to traffic damage and other effects, the remaining retroreflectivity will still be about 290 mcd/sq.m.-lux. CRF 2116 estimates the crash reduction factor due to increased brightness from 100 to 340 mcd/sq.m.-lux to be 53.2%. This implies an annual savings (benefit) of over $32,000 per mile in the comprehensive cost of prevented lost lives due to replacement of conventional edge lines with the new ultra-bright traffic stripe. Our long-term goal for the installed cost of the new traffic stripe is $1.50 per foot or $7,980 per mile. Comparing the savings (benefit) to the cost results in a payback time estimate of only 90 days.

TABLE 1 Benefit Cost Analysis Example

	Benefit Cost Analysis of New Traffic Stripe as Edge Line on Interstate Highways		
Item	**Description**	**Value**	**Source**
1	Fatalities on U.S. Interstates in 2020	5,129 deaths	NHTSA
2	Fraction of Fatalities at Nighttime	50%	National Safety Council
3	Fraction of Fatalities Due to Roadway Departures	50%	FHWA
4	Fatalities on U.S. Interstates in 2020 at Nighttime Due to Road Departures	1,282 deaths	Item 1 x Item 2 x Item 3
5	Lane Miles of U.S. Interstates	227,000 miles	USDOT
6	U.S. Nighttime Fatalities per Interstate Lane Mile in 2020	0.0056 deaths/mile	Item 4/Item 5
7	Comprehensive Cost of Each Death in 2021 Dollars	$10,700,000 per death	USDOT Guidance
8	Cost of U.S. Nighttime Roadway Departure Deaths per Interstate Lane Mile in 2021 Dollars	$60,441 per mile	Item 6 x Item 7
9	Proposed Minimum Retroreflectivity Standard	100 mcd/sq.m.-lux	FHWA
10	Typical Certified Test of Recent Prototype of New Traffic Stripe	29,000 mcd/sq.m.-lux	Road Vista/Gamma
11	New Stripe After Assumed 99% Degradation Rate	290 mcd/sq.m.-lux	0.01 x Item 10
12	CRF 2116 from 100 to 340 mcd/sq.m.-lux	53.2%	CRF 2116
13	Benefit of New Traffic Stripe per Lane Mile	$32,175 per mile	Item 10 x Item 6
14	Estimated Cost of New Stripe per Lane Mile	$7,920 per mile	$1.50/foot
15	Payback Time	90 Days	Item 14/Item 13 x 365

The analysis presented above is clearly much too conservative, since benefits of the new stripe are not even considered before it has degraded in performance by 99%, a very conservative value on its own. A more realistic benefit cost analysis will consider the integrated benefits of the new traffic stripe from installation until end of useful life. We have performed such an analysis using various assumed degradation rates to provide parametric benefit results for the new traffic stripe. We have also looked at the effect of missing our cost target to provide parametric cost results for the new traffic stripe. The values of items 1 through 10 in Table 1 were used in the parametric analysis and the CRF 2116 equation was applied for each day after installation including the effect of degradation. These parametric results are discussed in detail below.

Fig. 5 presents our parametric benefit cost analysis for the new ultra-bright traffic stripe. Four different installed cost values are considered and shown as dashed horizontal lines since they do not depend on elapsed time after installation. Three very high daily degradation rates are considered in this analysis as shown by the three cumulative benefit curves. The retroreflectivity is assumed to degrade from its initial value by a factor of $(1 - \text{rate})^{\text{n-days}}$. Thus, for example, after 30 days, the degradation factor would be $0.99^{30} = 74\%$ for the 1% daily degradation curve. Note that each cumulative benefit curve first increases rapidly, then levels off, and finally declines. Surprisingly, all three curves follow the same path for the first 350 days of so. This leads to an interesting conclusion that the payback time (crossover value of cumulative benefit and cost) is independent of the degradation rate and is very short indeed at about 50 and 200 days for the lowest and highest installed costs. Note also that the peak on each cumulative benefit curve represents the time period required for the degraded brightness of the traffic stripe to reach the proposed minimum retroreflectivity value of 100 mcd/sq.m.-lux, after which the CRF value is less than 1.0 and the cumulative benefit starts to decrease in value. This peak therefore represents the useful lifetime of the traffic stripe, which should be replaced at that point in time. Note also that the peak value of the cumulative benefit is many times greater than the cost of the traffic stripe for both assumed installed cost values. For example, the peak value of the magenta curve is over $305,000 per mile, representing a benefit to cost ratio of about 40X for the lowest assumed cost and about 10X for the highest assumed cost. Our team's long-term goal is to achieve a 10-year useful lifetime for the new traffic stripe, which will substantially increase the benefit to cost ratio to 64X for the target cost. A 10-year lifetime will require a daily degradation rate less than 0.15%, which corresponds to an annual degradation rate of less than 42% for presently demonstrated initial performance of 29,000 mcd/sq.m.-lux. We expect to improve the initial performance value significantly in the future as well, further boosting the benefit to cost ratio.

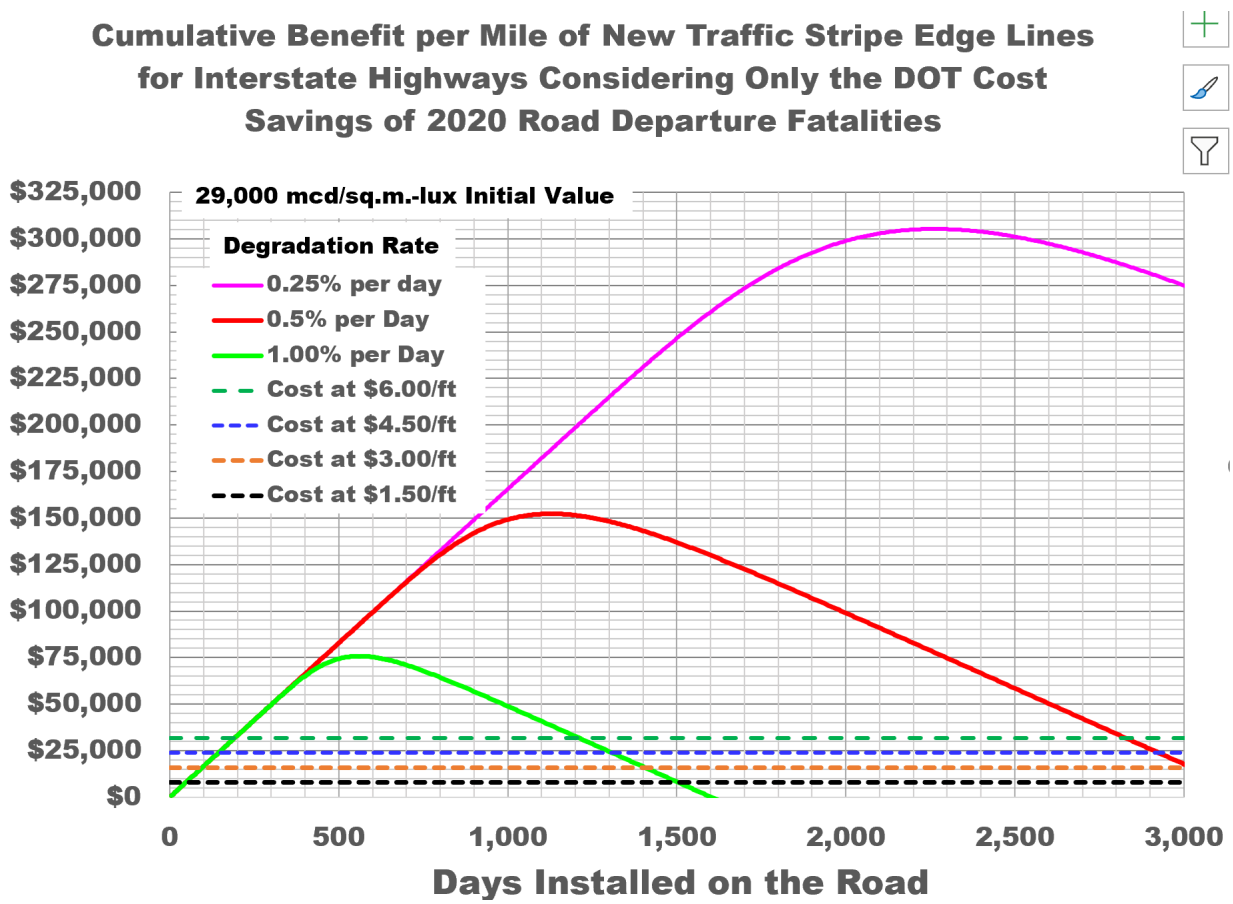

FIGURE 5 Parametric Benefit Cost Analysis of New Ultra-Bright Traffic Stripe

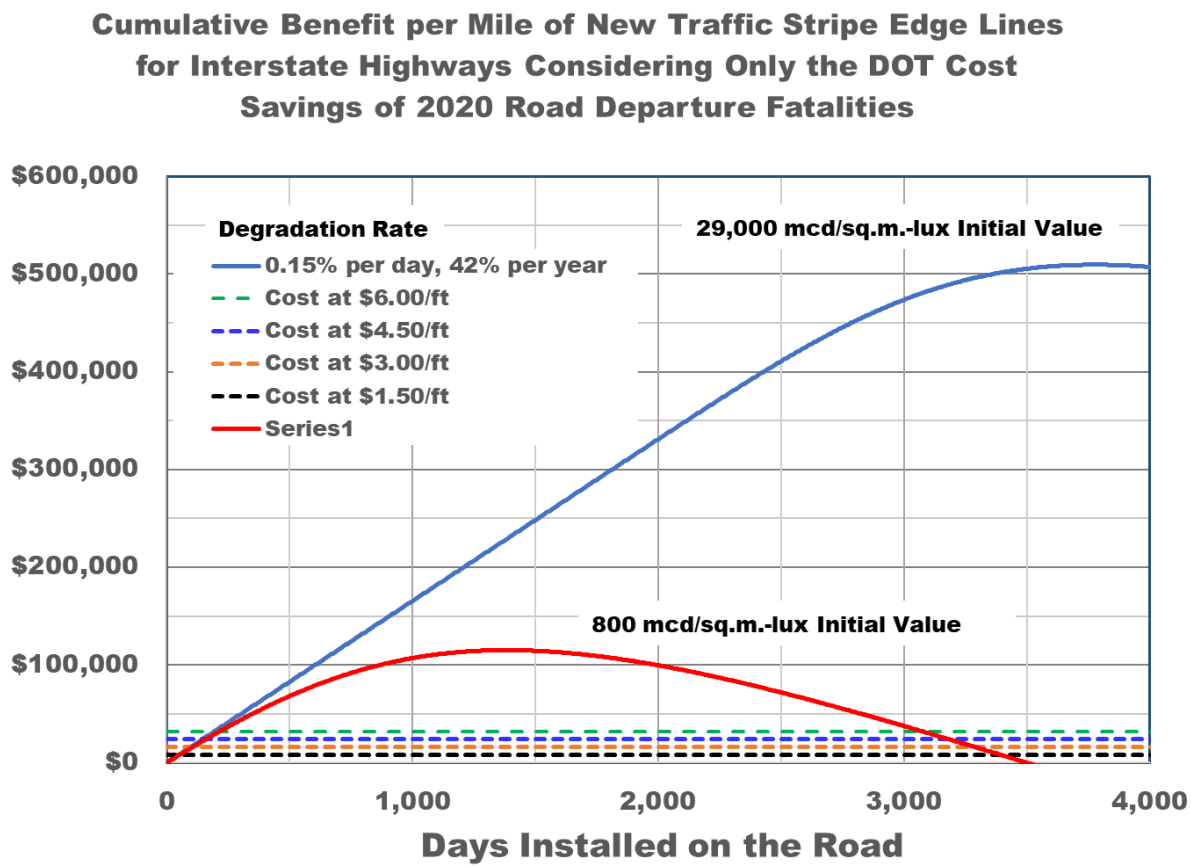

FIGURE 6 The Ultra-Bright Initial Retroreflectivity Increases the Cumulative Benefit

One of the members of our expert team suggested a comparison of the new traffic stripe versus the brightest existing traffic stripe technology, 3M's All Weather 380 tape product. Fig. 6 shows a comparison for an assumed 0.15% daily degradation rate (42% yearly degradation rate) for both products. While the initial cumulative benefits are similar, the much higher starting performance of the new traffic stripe leads to much higher cumulative benefits over the useful lifetimes of the products (where the peaks occur).

Another member of our expert team mentioned glare as a potential concern for traffic stripes. Fortunately, since the new traffic stripe is so efficient at retroreflecting the light back to the driver and sensors of the vehicle whose headlights illuminate the stripe, the amount of light reflected in other directions is minimized resulting in low glare for other drivers of other vehicles.

Another member of our expert team raised the issue of possibly too high a brightness for the new traffic stripe. Fortunately, as testing has shown, the brightness of the new traffic stripe is lower than the brightness of traffic signs using cube corner sheeting which are present on all the highways of the nation. The brightness of the new traffic stripe will not cause any visual discomfort at a value of 30,000-40,000 mcd/sq.m.-lux since traffic signs typically exceed 100,000 mcd/sq.m.-lux.

Another member of our expert team asked how we valued the benefit for interstate highway edge stripes. We applied the best available CRF 2116 to quantify the CRF value based on the improvement in edge line retroreflectivity compared to the pending U.S. standard for high-speed highways, namely 100 mcd/sq.m.-lux. We further assumed that 50% of the fatalities on interstate highways occurred at night and 50% of these involved highway departures, both estimates from the National Safety Council and the FHWA.

Further research into the benefits of the new traffic stripe is required beyond the scope of this small program.

CONCEPT AND INNOVATION

The fundamental concept employed in the present innovation is to use prismatic structures on both the top and bottom surfaces of a transparent polymer film to provide the brightest traffic stripe ever developed. The prismatic structures apply the principle of total internal reflection (TIR) to accept light from approaching headlights and retroreflect this light back to the driver and the sensors of the vehicle. Fig. 1 previously showed the geometry of the prismatic structures which accomplish this ultra-bright retroreflection. Under this program, we designed prototype traffic stripes which could be tested in a certified lab to verify the ultra-brightness we predicted. We then procured diamond-turning tooling to produce the top surface prismatic structure and we iterated on producing polymer prototypes incorporating this structure. We then laminated this top prismatic polymer film to commercially available cube corner sheeting which is widely used in traffic signs. Fig. 3 showed that early prototypes indeed proved the expected ultra-bright performance in certified lab testing. Over the course of the program, we refined our prototypes. The most important prototypes made to date use aliphatic thermoplastic polyurethane made by Lubrizol Advanced Materials for the top-surface prismatic structure and 3M Diamond Grade Cubed (DG^3) cube corner sheeting for the bottom surface prismatic structure. Six prototypes, each 10 cm (4 inches) wide by 91 cm (36 inches) long were fabricated as shown in Fig. 7.

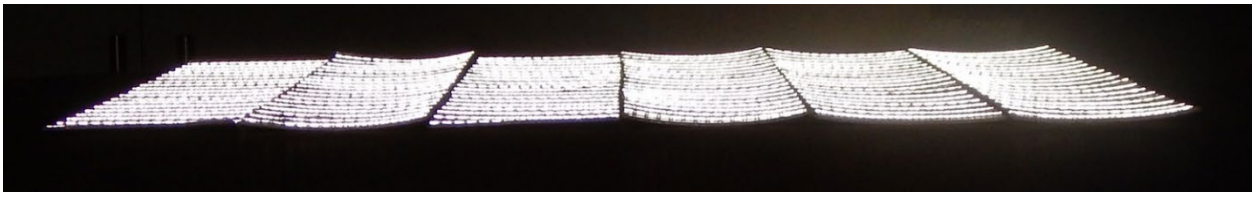

FIGURE 7 Prototypes Made with Lubrizol TPU Top Prismatic Film and 3M DG^3 Bottom Prismatic Film

As a benchmark for comparison, we procured the brightest current traffic stripe, 3M's All Weather AW380 white waffle tape. Fig. 8 shows one of the prototypes from Fig. 7 next to a 15 cm (6 inches) x 91 cm (36 inches) sample of the AW380 material. Fig. 9 shows the certified retroreflectivity measurements for these two traffic stripes.

FIGURE 8 3M AW380 on Left, New Ultra-Bright Stripe on Right

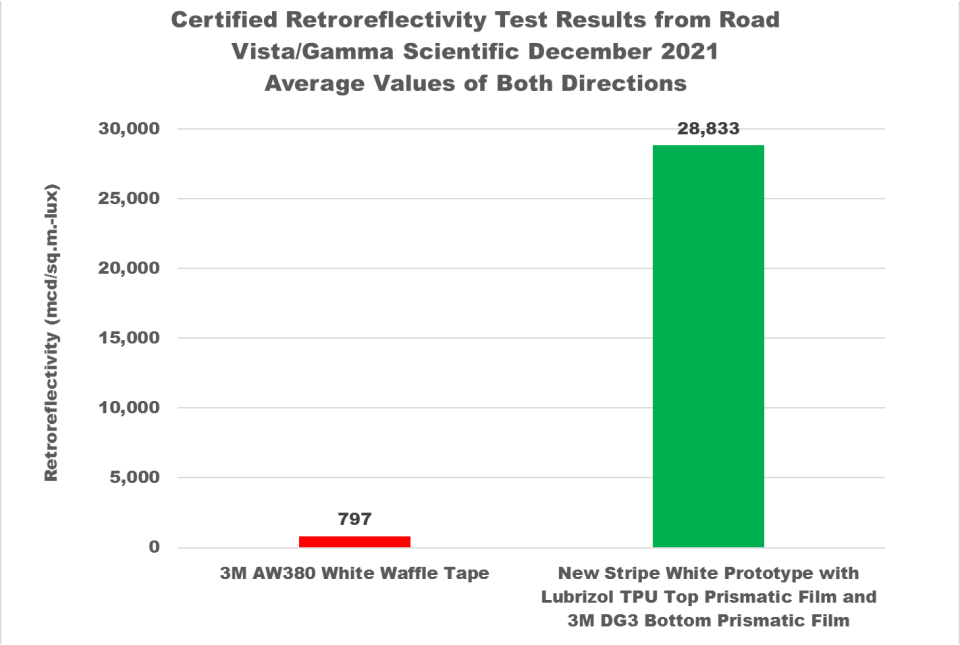

FIGURE 9 Certified Test Results

Therefore, the innovation represents the brightest traffic stripe ever tested. With its unprecedented brightness, the new traffic stripe offers the potential to make traffic stripes more visible to both human drivers and also sensors on connected and automated vehicles (CAVs). When fully developed and commercialized, this new traffic stripe could save many lives on the highways of the world.

The new traffic stripe can be made in a variety of colors by adding pigments to the transparent polymer. For example, Fig. 10 shows a yellow stripe which we made with silicone light-turning prisms over Orafol Oralite yellow cube corner prismatic retroreflective sign sheeting. Fig. 11 shows the certified retroreflectivity data for the yellow stripe compared to a white 3M AW380 stripe. Note that the yellow stripe is extremely bright, about 20X brighter than the 3M AW380 white stripe. Note also that the new traffic stripe works well with Orafol cube corner sign sheeting, a competitor with 3M's DG^3 cube corner sign sheeting. For laminated versions of our ultra-bright traffic stripe, any of the commercially available cube corner sign sheeting products can be used successfully. For our ultimate product, we plan to optimize and customize the cube corner prismatic pattern for the new traffic stripe application, rather than using products developed for the very different traffic sign industry. The optimized product will provide much better performance as well.

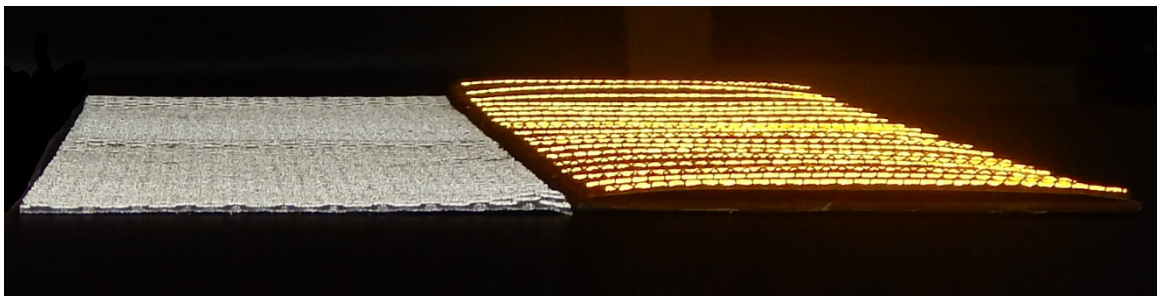

FIGURE 10 White 3M AW380 Stripe on Left, New Yellow Stripe on Right

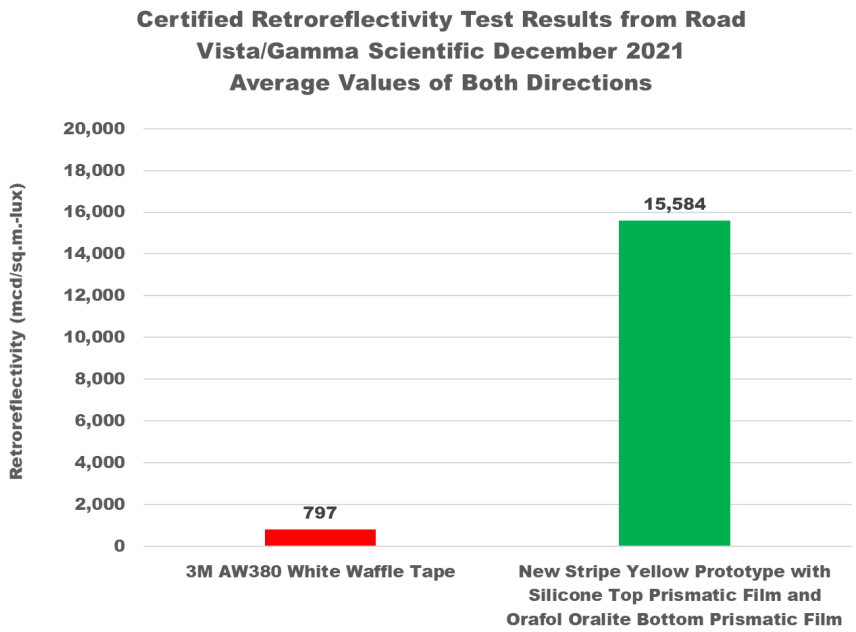

FIGURE 11 Certified Test Results

With the proper orientation of the light-turning prisms, the new traffic stripe can be used for various horizontal road surface applications, including white edge stripes, white or yellow centerline stripes, white or yellow skip stripes, crosswalk stripes, intersection stripes, etc. The new traffic stripe can also be used for vertical applications, as shown in Fig. 12. These vertical applications do not have the traffic damage or snowplow damage problems of horizontal applications, and may therefore represent the earliest market entry opportunity.

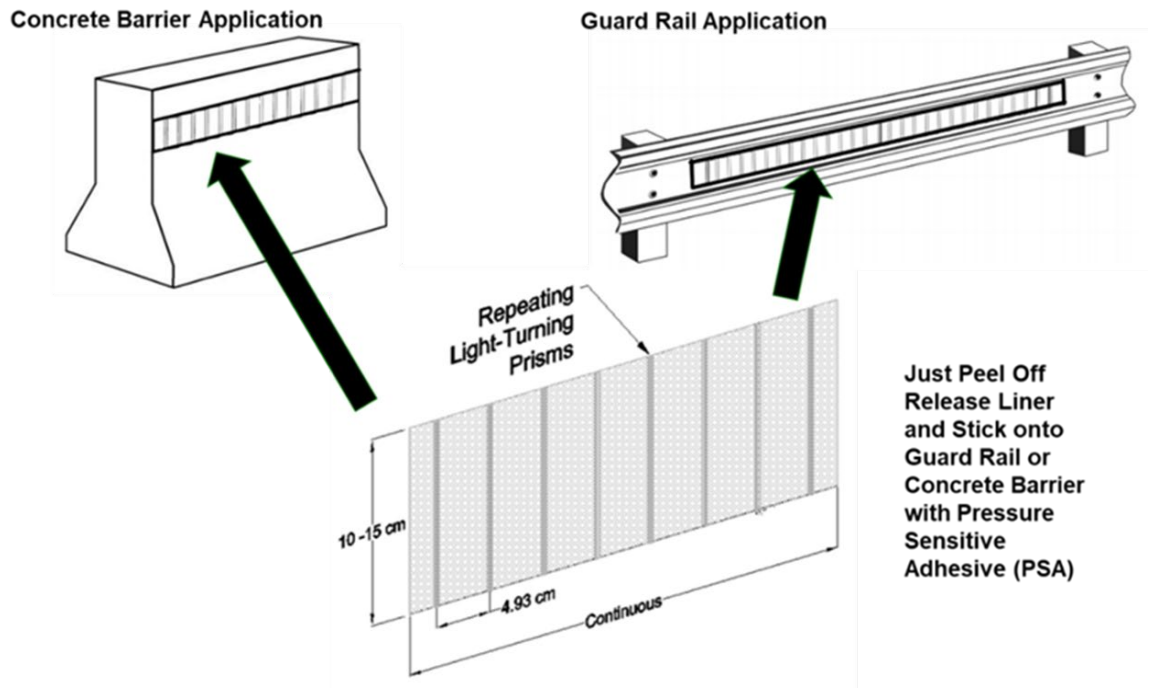

FIGURE 12 Vertical Applications of the New Ultra-Bright Traffic Stripe

We realize that the new traffic stripe must also be bright under daylight conditions. We have taken photographs of various prototypes outdoors during the day under sunlight and shade conditions, with typical photos shown in Fig. 13.

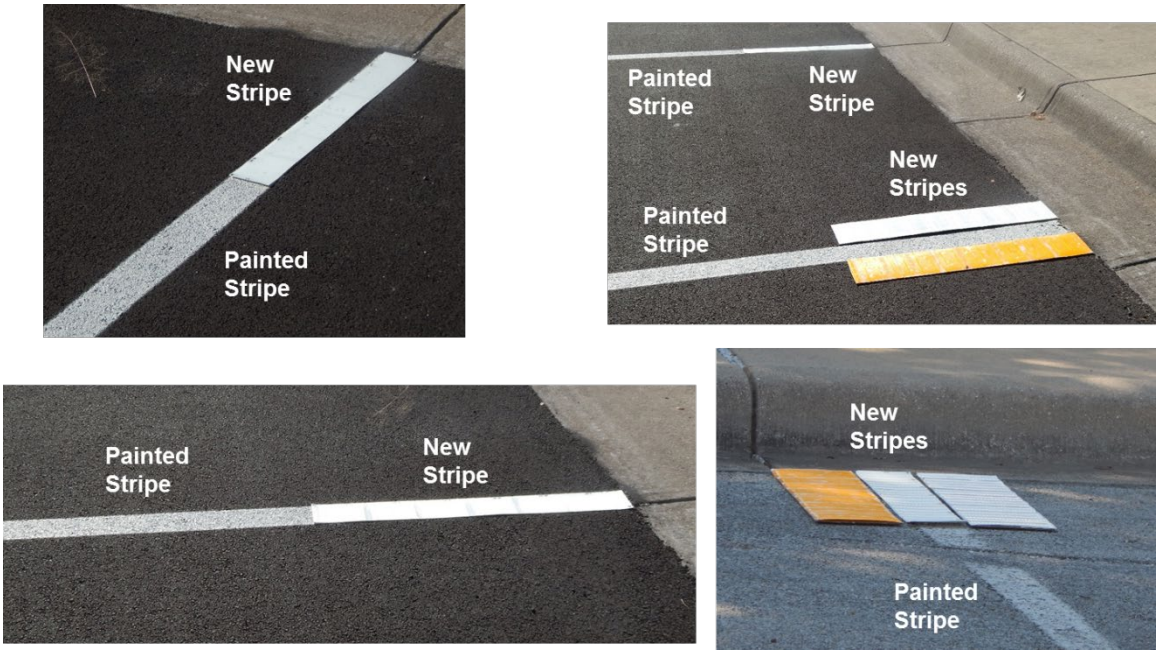

FIGURE 13 Daytime Photos of New Traffic Stripe Prototypes

Our motivation for developing this new traffic stripe technology was a request from a long-term friend and collaborator who directed NASA's space power program for many years. He closely collaborated on our long-term research, development, and commercialization of Fresnel lens photovoltaic concentrators for spacecraft power. A few years ago, he called me and said (paraphrasing him): "With all your work on prisms to redirect light, isn't there something you can do to make road stripes visible on dark rainy nights to keep older people like me from running off the road?" After looking at the problem for a couple of years without coming up with a good solution, we hit on the present approach which provides ultra-bright retroreflectivity when dry while also providing a significant level of brightness when wet, even when underwater. But we have since come up with much better solutions to incorporate into the new ultra-bright traffic stripe to make it very bright under both dry and wet conditions. We have not yet implemented these better solutions in actual hardware, since sophisticated diamond-turned tooling will be needed to produce the microstructured surfaces needed.

Fig. 14 shows a present, non-optimized 10 cm (4 inch) square prototype completely submerged underwater as evidenced by the floating wooden stick in the top photo. For comparison, a similarly sized 3M AW380 prototype is placed on the left next to the ultra-bright prototype on the right. The two bottom photos were taken with a distant flash camera illuminating the stripes in a dark room at two different angles. The brightness difference is dramatic. This underwater retroreflectivity is not due to the light-turning prisms but instead is due to the cube corner prisms between the widely spaced light-turning prisms. Our future stripes with optimized prismatic features (*2, 3*) will be many times brighter than the prototype in Fig. 14. We expect these future stripes to provide major crash-reduction benefits, but much additional research will be needed to quantify the benefits of much brighter traffic stripes on dark rainy nights. Our future business plan includes the first demonstration of the new traffic stripe configuration optimized for both wet and dry weather operation.

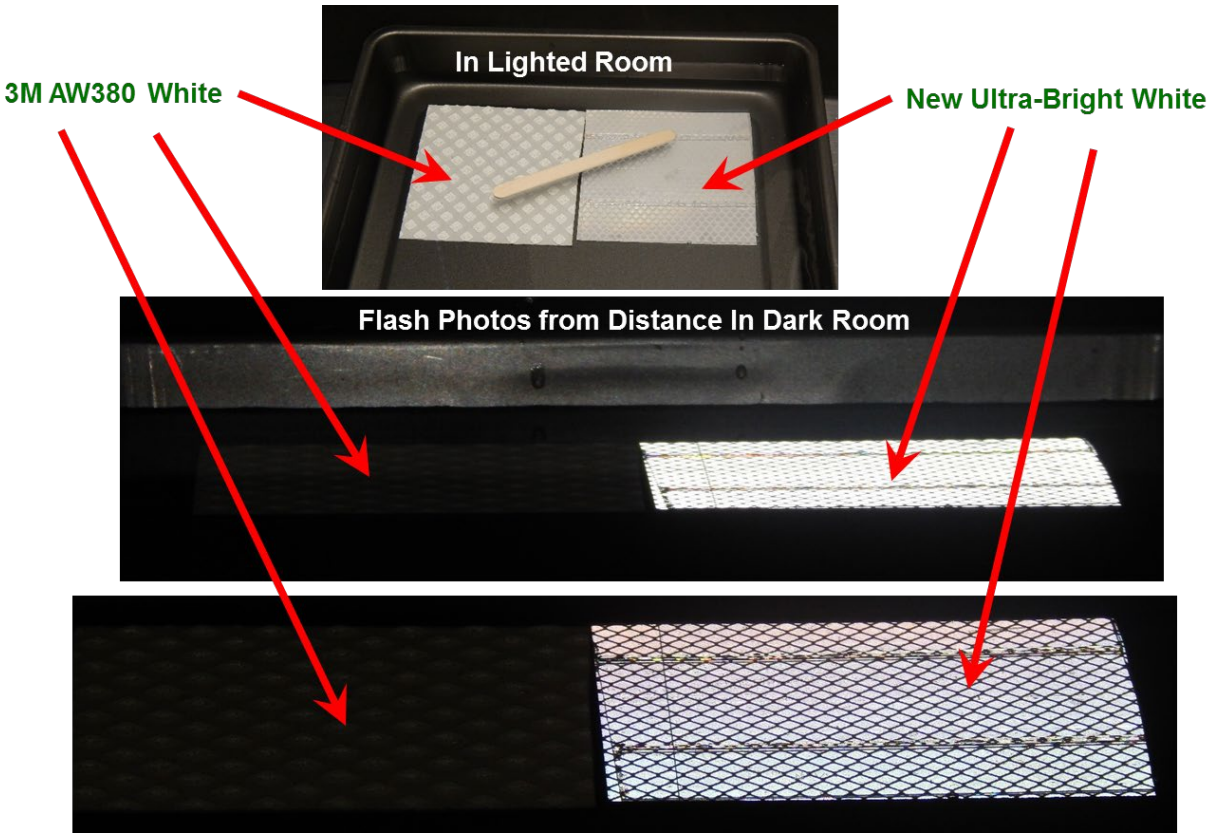

FIGURE 14 Underwater Brightness of Current Prototype

INVESTIGATION

The primary goal of the TRB IDEA program was to build and test for retroreflectivity the first fully functional prototypes of the new ultra-bright traffic stripe to verify that it would work as predicted. Our team successfully followed our proposed work plan to accomplish this goal within the first year of the program, as shown in Fig. 15 below. The vertical dashed line shows the date of this draft final report. The 16 tasks have all been successfully completed, as shown by the black bars filling the task bars.

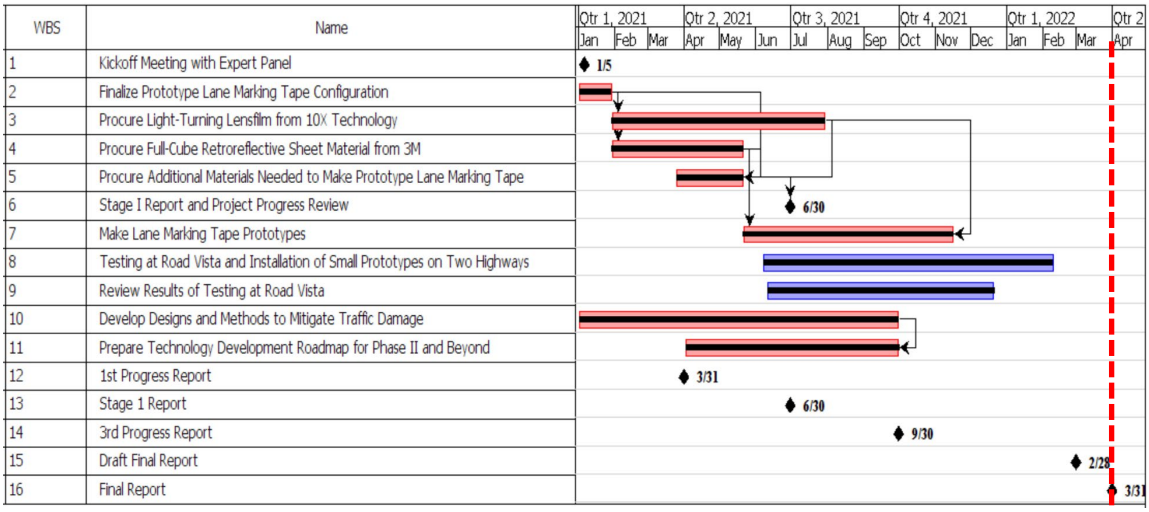

FIGURE 15 Our Phase I TRB IDEA Program Plan Which Was Successfully Implemented

We worked closely with our expert panel throughout the program, with frequent online meetings and reviews. We first designed the prototype traffic stripe which comprises a light-turning prismatic film on the top surface and a commercially available retroreflective cube corner prismatic film on the bottom surface, with a transparent adhesive between these two films. We then procured tooling and embossed thermoplastic polyurethane (TPU) parts from 10X Technologies. Unfortunately, 10X experienced difficulties in embossing the deep light-turning prisms. 10X was able to deliver some small TPU parts and some small cast polyurethane parts. We also procured some 3M Diamond Grade Cubed (DG^3) Type XI prismatic sheeting which is widely used in road signs. We found that the material had a much wider acceptance angle for non-perpendicular incident light in one direction (cross-web) than the other (down-web) and we therefore decided to cut strips of the material cross-web to use in the prototypes to offer better underwater performance. We laminated the 10X material to the 3M material using another 3M product, acrylic transparent pressure sensitive adhesive (PSA) #4910 as the bonding material. The first prototype achieved over 13,500 mcd/sq.m.-lux retroreflectivity in certified testing by Road Vista/Gamma Scientific (*5*). A second prototype used the cast polyurethane parts from 10X with the 3M sheeting to achieve over 13,800 mcd/sq.m.-lux retroreflectivity (*6*).

The 10X parts had noticeable defects which limited the performance of these early prototypes. We therefore procured new diamond-turned tooling from Film Optics in the U.K. to enable fabrication of light-turning prismatic sheets from alternate materials and processes. We made one prototype using the Film Optics tooling to cast epoxy light-turning prisms which achieved over 20,000 mcd/sq.m.-lux. We also made another epoxy prototype using home-made tooling which achieved almost 40,000 mcd/sq.m.-lux.

Our key TPU material supplier, Lubrizol Advanced Materials, next used the Film Optics tooling to compression-mold TPU parts for the light-turning prismatic film. Fig. 16 shows the Film Optics mold and early Lubrizol TPU parts made using the mold. Lubrizol molded about 40 TPU prismatic parts. We then made six prototype stripes (91 cm or 36 inches long) by laminating the Lubrizol prismatic film to the 3M film using 3M PSA #4905 as the bonding adhesive. One of these stripes was tested by Road Vista/Gamma Scientific at about 29,000 mcd/sq.m.-lux. Two of these stripes have been installed on two highways, one in North Carolina and the other in Texas.

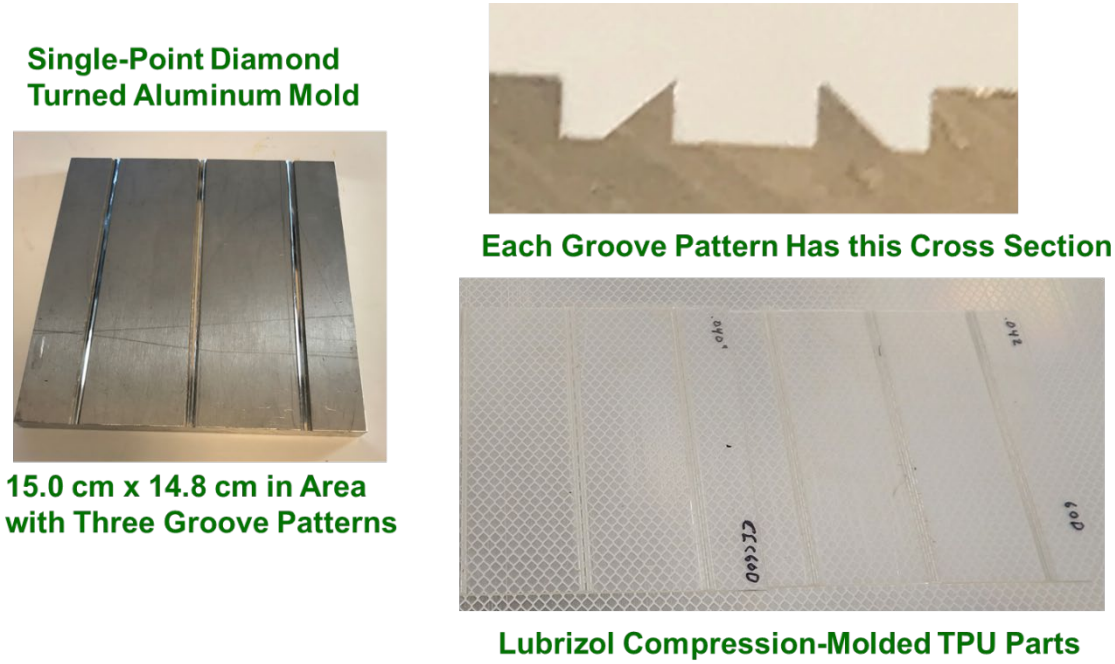

FIGURE 16 Diamond-Turned Mold and TPU Parts Made with Mold

We also cast silicone parts against the Film Optics mold and made one prototype using yellow-tinted Orafol Oralite cube corner sheeting to demonstrate that the new traffic stripe could be made in a variety of colors. This yellow stripe achieved over 15,500 mcd/sq.m.-lux in certified testing.

As a benchmark against which we could compare our certified test results, we also had Road Vista/Gamma Scientific test the currently brightest traffic stripe on the market, 3M's AW380 white waffle tape. It achieved about 800 mcd/sq.m.-lux, giving us a good point of comparison. The 3M AW380 has been proven to survive traffic and snowplows through three Chicago winters on Interstate 80 when installed in a pavement groove (*16*), with only about 3% loss in retroreflectivity from October 2016 to May 2019. We plan to learn from the 3M installation methods to provide a successfully path to install our new ultra-bright traffic stripes, including the use of a pavement groove for protection.

We have also developed designs for future versions of our new traffic stripe to mitigate traffic damage based on the successful 3M AW380 applications. These designs include raised traffic protection bars or ribs to encounter vehicle tires before the optically active elements of the traffic stripe. Fig. 17 shows on the left the 3M product on I-80 after three winters and on the right one of our concepts to implement traffic protection bars in both longitudinal and lateral directions for our new product. The raised features on the 3M AW380 utilize polyurethane, while our raised features will be made of thermoplastic polyurethane. Note that our concept has lateral raised bars between light-turning prisms and longitudinal raised bars with gaps to allow rainwater to drain off the stripe. Both the 3M product and our product will be installed in pavement grooves which are deeper than the total thickness of the installed stripes including mounting adhesive.

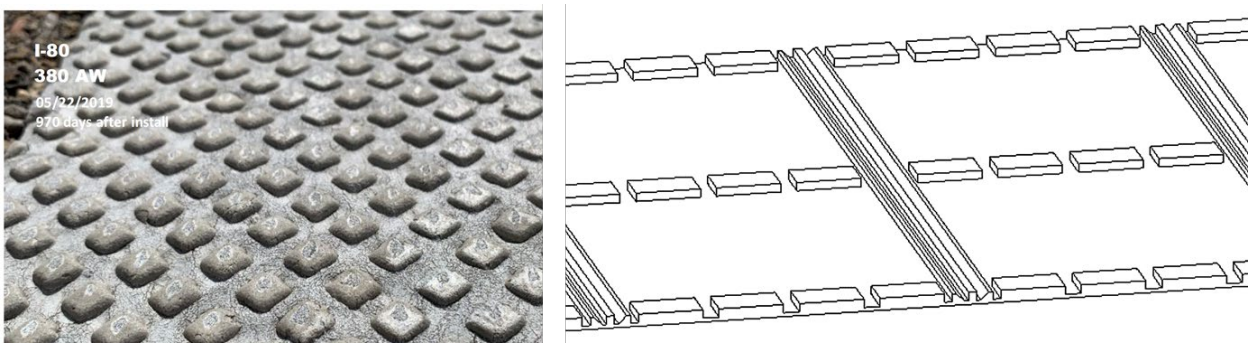

FIGURE 17 On Left, 3M's AW380 and, on Right, Our New Ultra-Bright Stripe.

The longitudinal bars shown in the drawing on the right of Fig. 17 do not block much light either arriving from the headlights or retroreflected back to the driver and sensors as shown in Fig. 18.

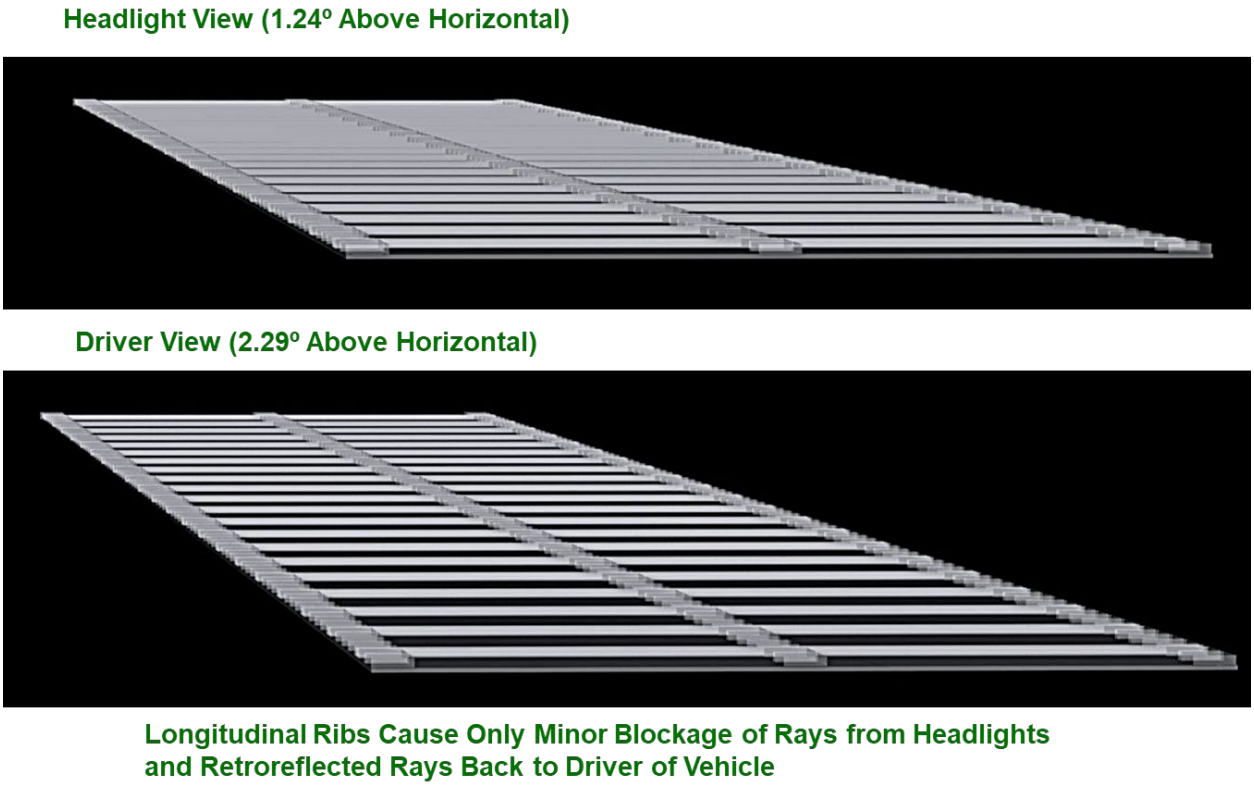

FIGURE 18 Headlight View and Driver View of Traffic Stripe with Longitudinal Ribs

We have also prepared a roadmap to complete the development and commercialization of the new ultra-bright traffic stripe as discussed in more detail in the following section of this report. We are working with an outstanding team including traffic safety experts, material providers, diamond tooling providers, manufacturers, installers, etc. We will need a significant investment and time to develop the ultimate product which will provide unprecedented retroreflectivity under both dry and extremely wet conditions. In fact, we have two different approaches to provide outstanding brightness when the new traffic stripe is completely submerged underwater (*2 and 3*).

While our primary motivation for completing the commercialization of the new traffic stripe technology is to save lives on American highways and roadways all over the world, another motivation is to provide a more environmentally friendly approach to traffic stripes. Our new stripe uses a non-toxic environmentally friendly polymer, TPU, which will become even more environmentally friendly in the future. Lubrizol Advanced Materials is working on a new formulation of TPU called BioTPU® which is made from plant-based materials. Eventually, it may be possible to make the new traffic stripe from a renewable material.

Perhaps more importantly, the new traffic stripe does not use any glass or ceramic beads, while competing traffic stripes, including the 3M AW380 tape and the more universally used painted stripes, employ such beads which are scattered into the environment in large quantities. Over 500,000,000 pounds of glass beads are dropped onto American highways each year (*17*). Some of these beads have been found to contain small amounts of toxic materials, including arsenic and lead (*17*), which can eventually leach into the groundwater. Therefore, wide adoption of the new prismatic traffic stripe could provide substantial environmental, safety, and health (ES&H) benefits to everyone in the manufacturing and supply chain, the installation and removal crews, and the countless residents near roadways.

We have also evaluated the advantages and disadvantages of a continuous tape product versus a segmented product for the new ultra-bright traffic stripe. Some of our advisors have mentioned the adhesion failures of some continuous traffic stripe tapes which led to long strips of material on the highway creating potential road hazards. A segmented tape product would mitigate such potential road hazard problems and would also offer benefits in terms of different mass-production processes such as compression molding and injection molding. Fig. 19 shows such a product and summarizes the advantages of this approach.

- Short segments can be mass-produced by compression or injection molding
- Short lengths can be easily installed on curves
- Short lengths don't create hazardous roll-up failures common with continuous tapes
- Short lengths create non-hazardous failures since each piece dislodged from the highway would be soft, pliable, and weigh less than 3 ounces per foot
- Installation and removal of repeating highway safety devices is not new – e.g., raised pavement markers (RPMs)

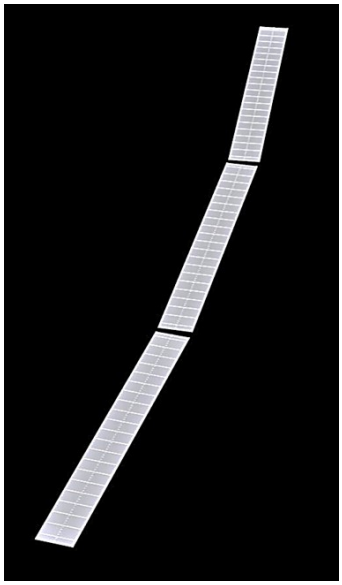

FIGURE 19 Advantages of Segmented Version of New Traffic Stripe

The new traffic stripe is much too bright to be measured on highways by most commercially available portable retroreflectometers, which typically have maximum measurement capabilities of 2,000-3,000 mcd/sq.m.-lux. To address this future need, our testing partner, Road Vista/Gamma Scientific, has run a number of tests using their portable retroreflectometers (Stripemaster® and Laserlux®) as summarized in Fig. 20.

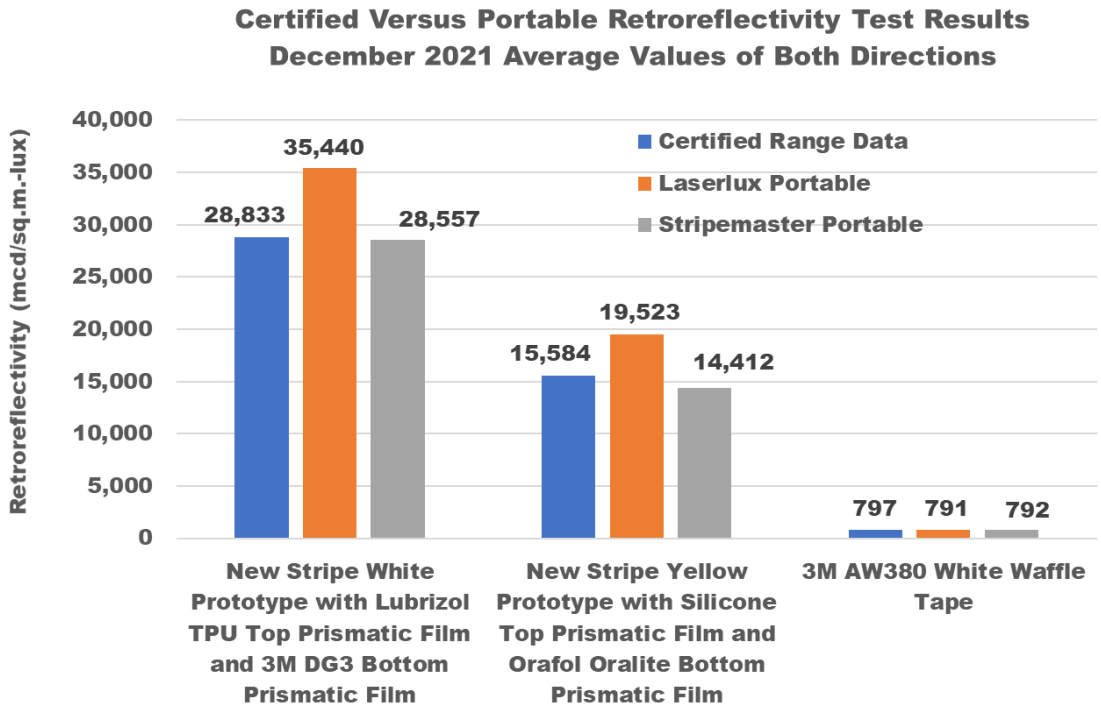

FIGURE 20 Certified Range Testing Versus Portable Retroreflectivity Measurements

These portable devices had modifications as needed for the greater brightness (e.g., 29,000 mcd/sq.m.-lux) of our stripes. They have found that by averaging multiple measurements along the length of the prototypes we have provided, they can get reasonable agreement with their more accurate lab measurements as shown in Fig. 20. The Stripemaster tests were run after holding the prototype stripes down flat with tape. The Road Vista/Gamma Scientific team is confident that future versions of their portable devices can meet the long-term needs for accurate in situ retroreflectivity measurements of our new ultra-bright traffic stripes.

The prototypes made under this Phase I TRB IDEA program are made from many different parts made of many different materials all bonded together with pressure sensitive adhesive (PSA), and are therefore not as robust as future commercial products will be. The bottom prismatic layer of the prototypes is cube corner sheeting meant for highway signs, not highway surfaces subject to traffic damage. Nonetheless, we have installed two of these prototypes on two highways as part of the Phase I program.

Fig. 21 shows some photos of the installation on Interstate 77 in North Carolina near the Virginia border. This white edge stripe is pieced together to form a 15 cm (6 inch) width installed in a pavement groove.

FIGURE 21 Prototype Installation in North Carolina

Fig. 22 shows the prototype installation in North Carolina after 6 weeks on the highway during which two blizzards occurred and more than a dozen snowplow passes occurred over the prototype. The stripe is still there and spot measurement with a handheld retroreflectometer (not accurate for this stripe as discussed above) shows a retroreflectivity above 1,000 mcd/sq.m.-lux. For future installations we plan to use a deeper pavement groove than on the North Carolina installation to further mitigate damage from traffic and snowplows.

Figure 22 North Carolina Installation After 6 Weeks, 2 Blizzards, and >12 Snowplow Passes

Fig. 23 shows a photo of the installation on the Chisolm Trail Parkway in Fort Worth, Texas. The prototype represents the right-most portion of the stripe, approximately one third of the total stripe length.

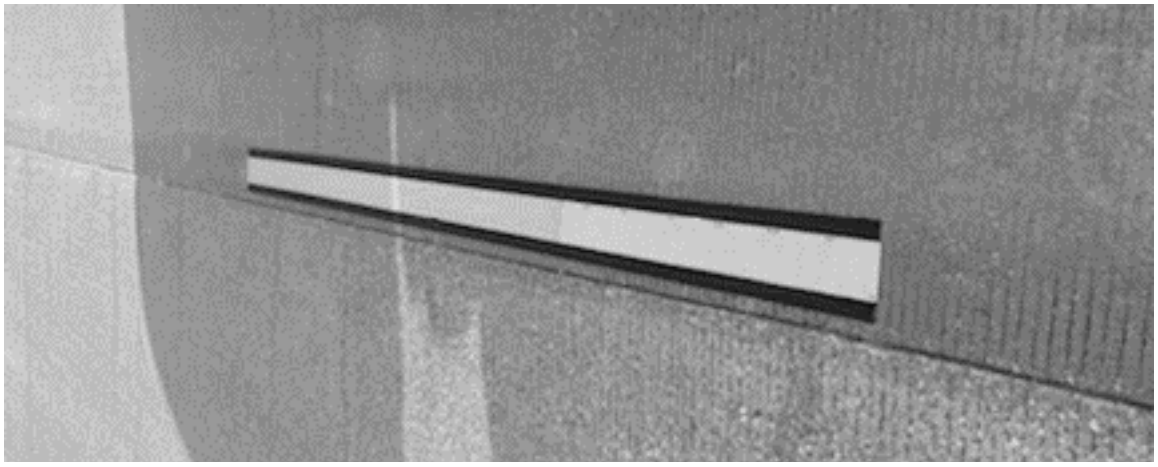

Figure 23 Prototype Installation in Texas

Fig. 24 shows the prototype installation in Texas after one month on the highway. It is installed as a portion of a skip stripe on a heavily used high-speed highway. The prototype is installed on top of the highway, not in a groove, and is therefore subject to more traffic damage than the North Carolina prototype. After large swings in temperature and a small ice storm, the Texas prototype is still measuring over 2,000 mcd/sq.m.-lux using a handheld retroreflectometer, which is not accurate for this stripe as discussed previously. This result is encouraging for sunbelt installations in the future. Perhaps pavement grooves will not be needed where snowplows are not used.

We have also provided all the reports for the program, including this draft final report, and we will incorporate the corrections and suggestions from the review of this draft report by our expert team of advisors in our final report.

Figure 24 Prototype in Texas after 1 Month

PLANS FOR IMPLEMENTATION

Our team has prepared a plan for implementation as shown in Fig. 25. This plan assumes we have the full funding required to accomplish a two-part plan to commercialize the new ultra-bright traffic stripe technology. We estimate our funding needs to be approximately $1,500,000-2,000,000, since tooling (diamond-turned masters and replicas for production) is expensive to mass-produce precise microstructured prismatic polymer films. To bring a product to market as quickly as possible, we plan to first commercialize a "minimum viable product (MVP)" which will have a higher price and lower performance than a "more ultimate product" which will follow the MVP about 1 year later.

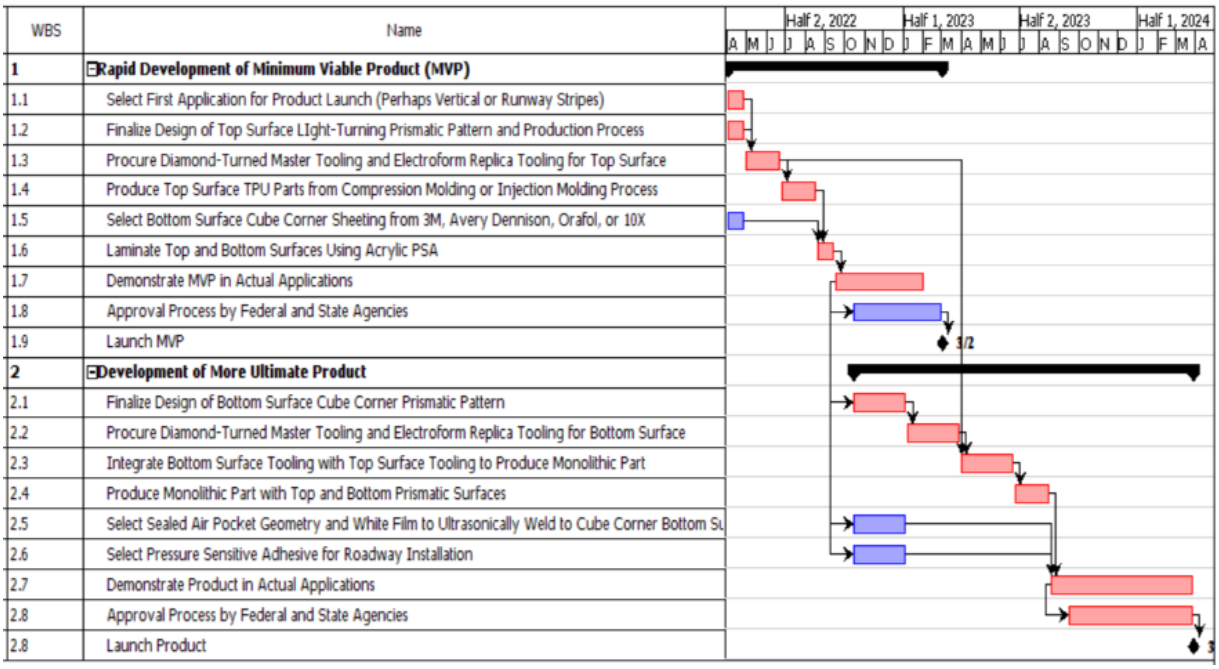

Figure 25 Plan for Commercialization of New Ultra-Bright Traffic Stripe

The MVP will use a new top prismatic film made from TPU like the most recent prototype stripes. But this film will use a production prismatic pattern including not only light-turning prisms but also structural ribs and bars for traffic protection and features optimized for very wet road conditions (*3*). The top prismatic film will also be sized and configured for mass production using either compression-molding (like the prototypes) or injection molding to provide discrete segments about 4 inches wide by about 36-48 inches long. These segments will later be laminated using acrylic PSA to commercially available cube corner sign sheeting from one or more of the leading providers (3M, Avery Dennison, Orafol, et al.) or from more recent entries into this market like 10X. The cost of purchasing the cube corner sheeting and the processing cost for lamination will be added to the cost of producing the top prismatic film, resulting in a more expensive traffic stripe product than a later more ultimate product. The laminated product will also have lower performance and be less durable than a more ultimate product. Nonetheless, getting the MVP to market early is important to introduce the new technology to the stakeholders in traffic safety, including the U.S. Department of Transportation (DOT) and the state DOTs. We will choose an application for the MVP which will tolerate a higher price and reduced durability, such as vertical applications on guardrails and concrete barriers or aviation applications such as runway stripes or taxi stripes. These applications have less traffic damage and the ultra-brightness will have greater value to the customers. We hope to launch this product within one year of beginning our commercialization program.

We plan to develop the more ultimate product beginning about six months into the commercialization program with a launch date at the end of the second year of the program. The more ultimate product will combine the top surface prismatic pattern of the MVP will a custom back surface cube corner pattern in a monolithic TPU film with higher performance and much higher durability and a significantly lower price than the MVP. This second product will be intended for the road surface stripe applications representing a multi-billion-dollar market.

Since we are novices in the traffic safety industry, we are relying heavily on the experience and expertise of our advisor and collaborator, Dr. Paul Carlson, to guide our commercialization activities including AASHTO and NTPEP testing.

CONCLUSIONS

The principal conclusion of this TRB IDEA project is:

- The new ultra-bright traffic stripe **performs as predicted**, providing a retroreflectivity **hundreds of times brighter than conventional traffic stripes**. This conclusion was established by making **the first fully functional prototypes** of the new traffic stripe and testing these prototypes in a certified laboratory.

Supporting conclusions include the following:

- The new traffic stripe can save lives due to its ultra-bright visibility to both human drivers and the sensors on connected and automated vehicles (CAVs).
- The new traffic stripe offers a rapid payback period due to its ability to reduce crashes, especially nighttime road departure fatalities.
- The new traffic stripe will provide a very high (20-40X) benefit to cost ratio if degradation rates below 42% per year can be achieved.
- The new traffic stripe offers exceptional brightness even when underwater, thereby offering visibility on dark stormy nights.
- The new traffic stripe uses only an environmentally friendly polymer for retroreflectivity, eliminating the need for glass or ceramic beads, which are currently dropped on American highways in quantities of 500,000,000 pounds per year, with such beads sometimes containing small amounts of toxic materials like arsenic and lead.
- Improvements to the new traffic stripe to mitigate traffic damage, improve performance, and reduce cost have been identified for future implementation.
- The new traffic stripe can be used in vertical applications like guardrails and concrete barriers as well as horizontal applications like edge lines, skip stripes, crosswalk stripes, etc.
- A roadmap for completing the development and commercialization of the new traffic stripe has been created, requiring additional investment and time to fully realize its potential on American highways and later the roadways of the world.
- Two U.S. patents have already issued for the innovative ultra-bright traffic stripe, with others pending. Intellectual property will help secure future investment to complete the development and commercialization of the new technology.

INVESTIGATORS' PROFILES

The prime contractor for this TRB IDEA program was **Mark O'Neill, LLC (MOLLC)**, a small business in Fort Worth, Texas. The principal investigator for the program was Mark O'Neill, president of MOLLC. O'Neill is an aerospace engineer with many decades of experience in solar power for both space and ground applications. His specialty is prismatic optics, which are used to focus sunlight onto small solar cells in space and on the ground. O'Neill has authored 21 U.S. patents with more pending on refractive and reflective solar concentrators, prismatic covers and windows for solar cells, deployable space solar concentrators, daylighting systems, and most recently ultra-bright traffic stripes. O'Neill has published over 200 technical papers and reports and has won several awards, including an R&D 100 award with NASA on a novel photovoltaic concentrator system. O'Neill has proposed, won, and managed many NASA contracts related to advanced space solar power systems, which have performed well in space.

Key subcontractors provided outstanding support for this TRB IDEA program:

- **10X Technologies** made the first TPU and cast PU parts for prototypes. Bob Pricone is the founder and head of 10X and has decades of experience in traffic safety products at Stimsonite and Avery Dennison.
- **Film Optics Ltd** (U.K.) made the diamond-turned molding tools for additional parts. Paul Surguy is managing director of Film Optics and has many years of experience in developing and mass-producing prismatic optical products for solar power, lighting, and other applications.
- **Lubrizol Advanced Materials** provided guidance on their TPU materials and produced the compression-molded TPU parts for our prototype traffic stripes. Matt Mapus and Jason Schaner led this valuable effort for Lubrizol.
- **Road Vista/Gamma Scientific** performed certified retroreflectivity testing of multiple prototypes in their laboratory according to ASTM Standards D4061, E809, and E1710, and CEN Standard EN1436, and provided advice on future testing of installed ultra-bright stripes. Eric Nelson led this valuable effort at Road Vista/Gamma Scientific.
- **Dr. Paul Carlson**, an internationally recognized expert on traffic safety, provided invaluable advice about the new traffic stripe technology, and coordinated the installation of prototypes by **TRP Infrastructure Services**.

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APPENDIX: RESEARCH RESULTS

Sidebar Info
Program Steering Committee: NCHRP IDEA Program Committee
Month and Year: March 2022
Title: A Retroreflective Road Lane Marking Tape 1,000X Brighter than Existing Technology
Project Number: NCHRP 228
Start Date: January 1, 2021
Completion Date: March 31, 2022
Product Category: Retroreflective Traffic Stripe
Principal Investigator:
Name, Title: Mark O'Neill, President
E-Mail: markoneill@markoneill.com
Phone: 817-380-5930
TITLE: Ultra-Bright Traffic Stripe

SUBHEAD: The first fully functional prototypes were tested in a certified lab at 130-400 times brighter than conventional stripes.

Answer the following questions in 550–650 words.

WHAT WAS THE NEED?

Most conventional traffic stripes still use a century-old technology: glass beads dropped into paint to provide a modest level of retroreflectivity under dry conditions which is spoiled by wet conditions. New technology can provide much brighter traffic stripes for both human drivers and for sensors on connected and automated vehicles (CAVs) to reduce crashes due to lane departures and road departures. Eliminating the use of glass or ceramic beads in traffic stripes offers major environmental and health benefits. Brighter traffic stripes, especially on dark wet roads, will save many lives.

WHAT WAS OUR GOAL?

Our principal goal was to demonstrate for the first time the predicted ultra-bright retroreflectivity of a totally new approach to traffic stripes using prismatic surfaces on a transparent polymer film. Supporting goals were to design, tool, and make prototypes and to test these prototypes in a certified lab.

WHAT DID WE DO?

We designed prototypes, procured diamond-turned tooling to make the top prismatic surface, made top surface prismatic parts, laminated these top surface parts to commercially available cube corner retroreflective sheeting, and tested prototypes in a certified lab, fully verifying unprecedented retroreflectivity hundreds of times higher than for conventional traffic stripes. We were advised by experts from the TRB, state DOTs, and the traffic safety industry.

WHAT WAS THE OUTCOME?

We proved the unprecedented optical performance of the new traffic stripe technology. We also developed concepts for making later production traffic stripes more robust against traffic damage. We installed two early prototypes on roadways in Texas and North Carolina. We developed a roadmap to complete the development and commercialization of this exciting new technology.

WHAT IS THE BENEFIT?

We performed benefit cost analyses which showed that the new traffic stripe would have a payback period of just a few months based on USDOT crash reduction factor (CRF) data and statistical value of saved human lives. The benefit to cost ratio was shown to be very large. Most importantly, a large number of lives could be saved by widespread adoption of the new ultra-bright traffic stripe technology.

LEARN MORE
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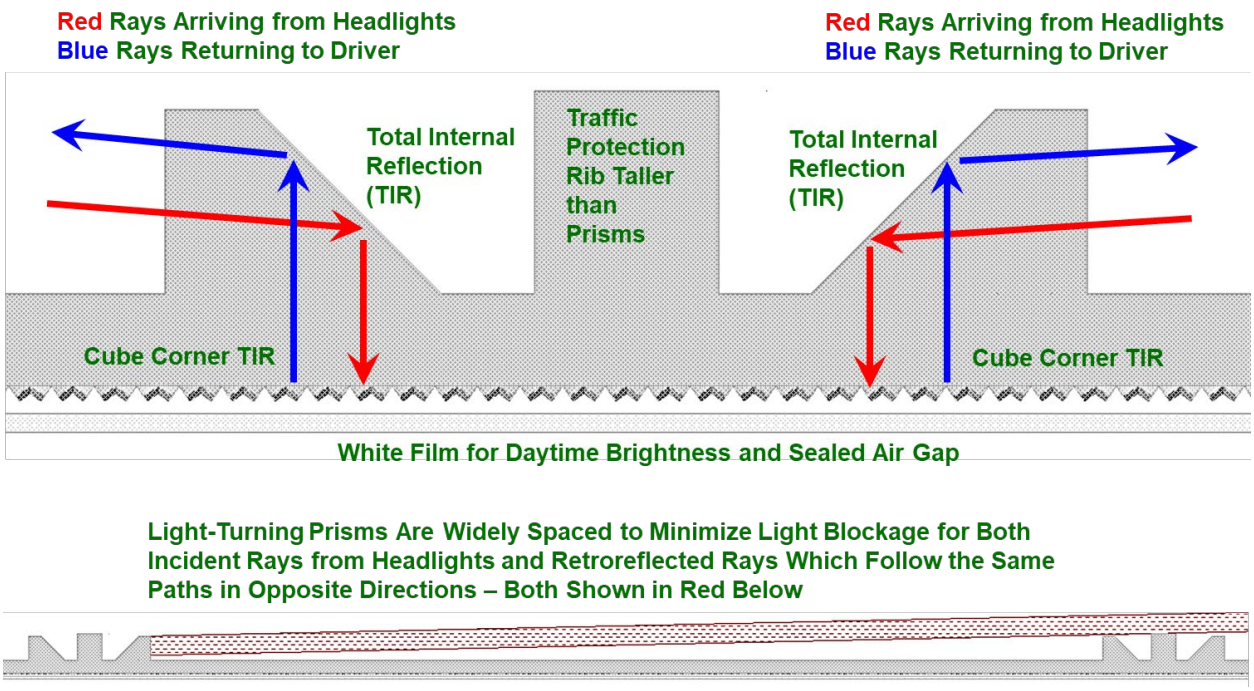
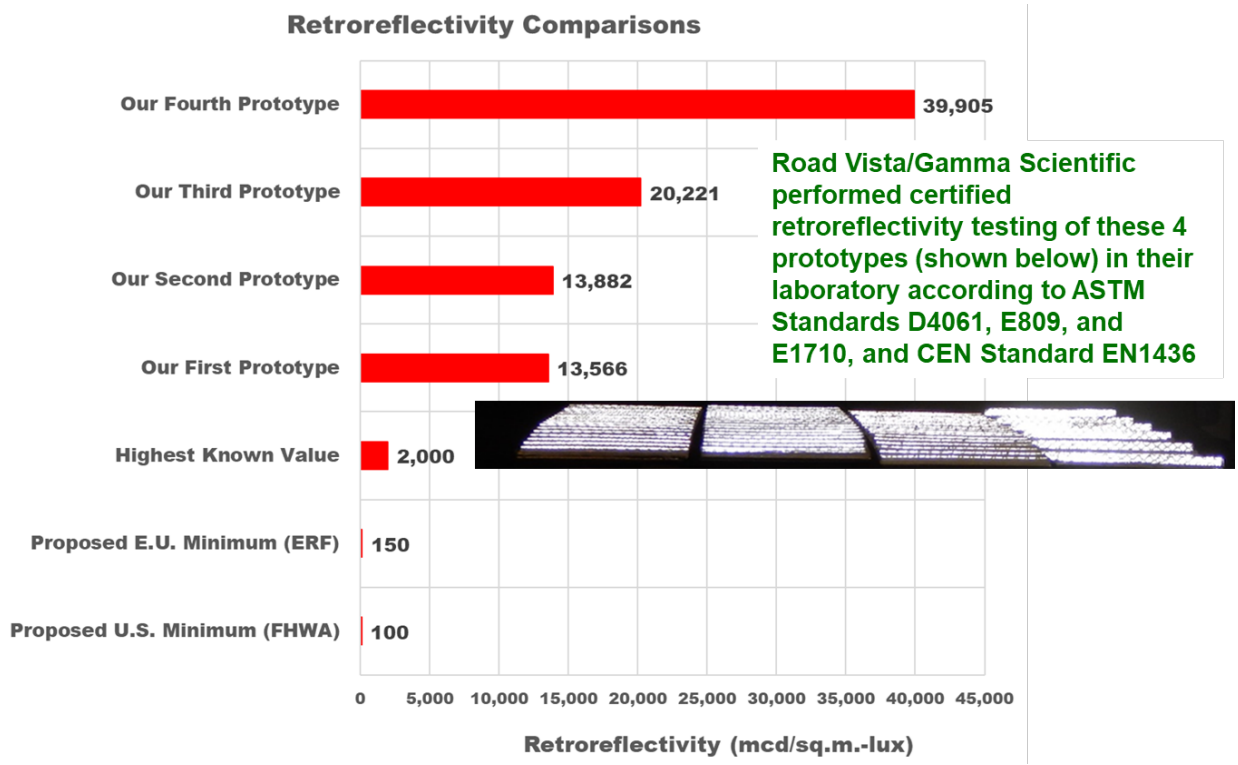
IMAGES
See next page.



How the New Traffic Stripe Works



Certified Retroreflectivity Measurements of Prototypes of New Traffic Stripe