University Transportation Research Center - Region 2

Final Report

Innovative Roadway Light Source and Dye Combinations to Improve Visibility and Reduce Environmental Impacts

Performing Organization: Rensselaer Polytechnic Institute

April 2013

Sponsor:
Research and Innovative Technology Administration / USDOT (RITA)

University Transportation Research Center - Region 2

The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

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The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

Education and Workforce Development

The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

Technology Transfer

UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

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Project Title: Innovative Roadway Light Source and Dye Combinations to Improve Visibility and Reduce Environmental Impacts

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REGION II
UNIVERSITY TRANSPORTATION RESEARCH CENTER

FINAL REPORT

Innovative Roadway Light Source and Dye Combinations to Improve Visibility and Reduce Environmental Impacts

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Sky glow light pollution is caused largely by reflected light off of roadway and other surfaces. The authors investigated the feasibility of a system consisting of a specialized LED streetlight and a dye-based roadway surface coating that would reduce sky glow, but still provide adequate illumination of objects in the road. As envisioned, the streetlight would produce white light with narrow-band LEDs of red, green, and blue wavelengths. The roadway surface coating would use three dyes that would selectively absorb the specific wavelengths produced by the streetlight. This investigation examined the optical properties of green and blue absorbing dyes. The dyes, when in their liquid states, did selectively absorb light at the expected wavelengths. However, the dyes did not selectively absorb light when applied as a surface coating, so appropriate encapsulants would need to be developed for subsequent implementation. Also, issues of stability over time, cost, and safety were identified. A number of significant hurdles would need to be overcome before this could become a practical method of reducing sky glow from roadway illumination systems.</td></tr>
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Executive Summary

Sky glow light pollution is caused largely by reflected light off of roadway and other surfaces. The authors investigated the feasibility of a system consisting of a specialized LED streetlight and a dye-based roadway surface coating that would reduce sky glow, but still provide adequate illumination of objects in the road. As envisioned, the streetlight would produce white light with narrow-band LEDs of red, green, and blue wavelengths. The roadway surface coating would use three dyes that would selectively absorb the specific wavelengths produced by the streetlight. This investigation examined the optical properties of green and blue absorbing dyes. The dyes, when in their liquid states, did selectively absorb light at the expected wavelengths. However, the dyes did not selectively absorb light when applied as a surface coating, so appropriate encapsulants would need to be developed for subsequent implementation. Also, issues of stability over time, cost, and safety were identified. A number of significant hurdles would need to be overcome before this could become a practical method of reducing sky glow from roadway illumination systems.

Introduction

Streetlights are a necessary element for roadway safety, but they have a negative impact on the environment in two ways. First, they consume electricity, which results in power plant emissions. According to a market survey, outdoor stationary lighting consumes 118 TWh/ year of electricity in the U.S.[1] Based on average emission rates, this would result in 65 million metric tons of carbon dioxide per year being added to the atmosphere.[2]

Commercially available LED streetlights have the potential to reduce streetlight power demand. An LRC study tested streetlights for local roads and found that the LED models required on average 6% or 24% less power depending on their layout, and one of the LED models tested had a 41% lower power demand per mile than the incumbent high pressure sodium (HPS) streetlight tested while still meeting IESNA RP-08 roadway lighting criteria.[3] As LED efficacies and light output improve, the power demand per mile is expected to improve even further.

The second problem caused by outdoor lighting is light pollution. There are three types of light pollution: light trespass, glare, and sky glow. The first two can be minimized with proper lighting design, but the last type is inherent to current outdoor lighting and is the problem addressed in this study. It is caused by outdoor electric light at night that radiates upward (either directly from a luminaire or reflected off a surface) and scatters off of atmospheric gas molecules, aerosols, and dust so that a portion of it is redirected toward the ground.

Sky glow increases the luminance of the sky at night. As noted by National Geographic magazine, "[M]ost of humanity lives under intersecting domes of reflected, refracted light, of scattering rays from overlit cities and suburbs, from light-flooded highways and factories."[4] It is an especially relevant issue for U.S. Department of Transportation's Region 2 because large areas of New

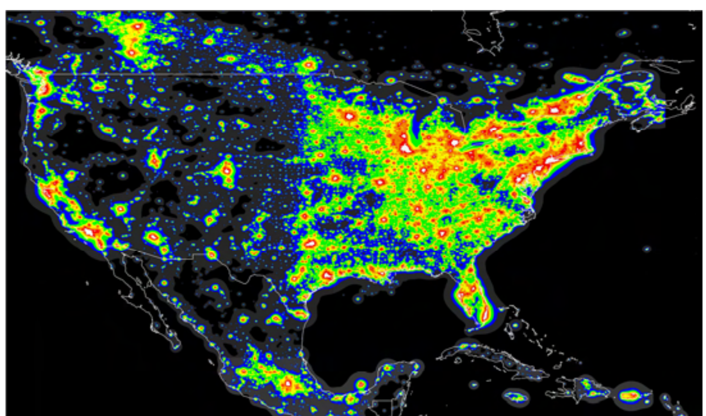


Figure 1: Artificial Night Sky Brightness. Colors correspond to ratios between the artificial sky brightness and the natural sky brightness of: <0.01 (black), 0.01-0.11 (dark-gray), 0.11-0.33 (blue), 0.33-1 (green), 1-3 (yellow), 3-9 (orange), 9-27 (red), <27 (white).

York and New Jersey suffer from the highest amounts of sky glow in the United States; San Juan in Puerto Rico also has high sky glow values, as shown in Figure 1.[5]

There is little scientific evidence of the direct impact of sky glow on human health or the environment, possibly because this is a relatively young field of research. Among some animals, sky glow is believed to affect reproduction, foraging and predation, and migration. [6,7] At least one scientist suggests that sky glow might be contributing to the global declines in population size and diversity of frogs and toads.[8] Some have suggested a correlation between sky glow and human breast cancer, but such links are unproven and controversial at best.[9] As sky glow increases or encroaches, astronomers must build larger terrestrial telescopes or use a space-based one in order to maintain their observing power.[10]

Sky glow has been gaining increased attention from the public and the press over recent years not only because of these potentially detrimental effects on humans, the environment, and astronomy, but because it decreases the visibility of stars by the unaided eye. For example, in the outer boroughs of New York City (Brooklyn, Queens, Staten Island, and The Bronx), a maximum of 50 stars are visible, compared to the several thousand visible in the natural night sky.[11] The biologist Edward O. Wilson popularized the "biophilia hypothesis," which posits that humans have an instinctive bond with nature.[12] According to this hypothesis, it is possible that disrupting this bond may have negative effects on peoples' psyches.

No matter the reason for it, there does seem to be increasing concern about sky glow, as evidenced by the number of municipalities specifying full-cutoff outdoor fixtures and the fact that over 90 manufacturers participate in the International Dark-Sky Association's Fixture Seal of Approval Program.[13]

Current LED streetlights do not reduce sky glow light pollution compared with the incumbent high-pressure sodium (HPS) luminaires with the same cutoff classification. Indeed, LED lighting may cause slightly more sky glow than HPS lighting because shorter wavelength light (found in greater proportion in white light, such as from LEDs) can result in somewhat more sky glow (about 10%-15% under the worst conditions) than longer wavelength light (found in greater proportion in the yellow-orange light from HPS sources).[14]

A number of solutions have been proposed to address sky glow:[15]

- Use light only when and where it's needed
- Use only as much light as needed
- Shine lights down, not up

Figure 2: This nighttime aerial photograph of Chicago illustrates that a significant portion of sky glow is a result of reflected streetlighting.

While these measures are reasonable and should be observed for most outdoor lighting installations, the degree to which they would reduce sky glow is unknown. The reason is that a significant portion of light pollution is caused by light reflected from the ground, not light emitted directly from outdoor lights. It is reasonable to assume that outside of urban centers most light at night is from streetlights, and a 1972 study found that two to three times more sky luminance is due to light reflected off the pavement than directly emitted by streetlights.[16] Recent codes and regulations calling for full cutoff streetlights (which eliminate direct uplighting) means that the proportion of reflected light pollution is likely to be even higher now. Figure 2 illustrates that a significant portion of upward light comes from the reflection of streetlights off of pavement surfaces.[17] The color of the lighting on the clouds indicates that the light source is likely to be high-pressure sodium, which is predominantly used for roadway and area lighting. A close examination of the photo shows that the sources of luminance are large surfaces such as roadways, not small point sources such as streetlights.

Research Approach

The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute examined the potential of harnessing the unique properties of LEDs to create a new streetlight system that reduces light pollution by reducing the light reflected from roadway and parking lot surfaces, which is a significant source of sky glow and cannot be eliminated using current lighting techniques. The concept, originated by the authors, was to pair an LED streetlight that produces white light with a combination of red, green, and blue LEDs through color mixing (in the same way that a television monitor produces white light with a combination of red, green, and blue pixels) with a road surface coating that incorporates dyes to absorb those specific wavelengths but reflect most others. Examples of LEDs and corresponding potential dyes are shown in Figure 3.

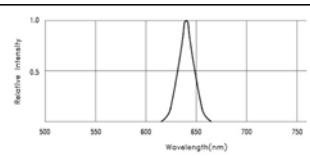
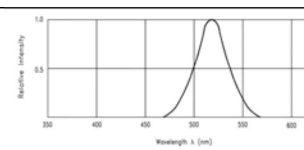
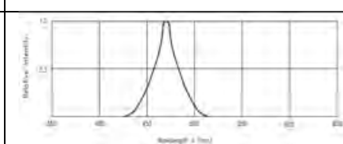
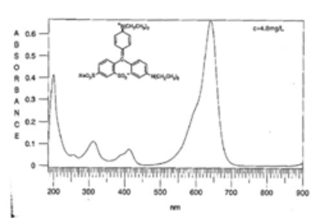
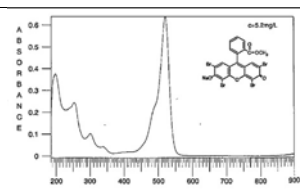
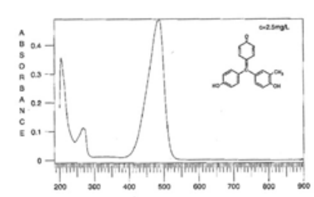
	Red	Green	Blue
LED Emittance[18]	 Peak Wavelength: 630 nm	 Peak Wavelength: 527 nm	 Peak Wavelength: 473 nm
Dye Absorbance[19]	 Patent Blue VF/ Acid Blue 1 Max absorbance: 635 nm	 Methyl Eosin/ Solvent Red 44 Max absorbance: 520 nm	 Rosolic Acid/ Aurin Max absorbance: 482 nm

Figure 3: LED spectral power distribution and dye absorbance for red, green, and blue peak wavelengths. The x-scales in the various diagrams are different so the peaks do not align visually, but the peak wavelengths for the LEDs and dyes are within 10 nm of one another for each color.

If fully realized, the concept could result in a road that reflects little light from the streetlights, but would reflect most wavelengths of sunlight during the day. At night, objects on the road will be visible because they will be illuminated with white light, but the road would appear relatively dark. This would increase the luminance contrast between an object in the road and the roadway surface, making obstructions and hazards even more visible. Striping along the center and edge of the road will indicate the travel pathway to drivers. Car headlights will illuminate the road normally because these produce a broad spectrum white light.

An alternative method of reducing light pollution would be to use a black pigment on the road surface, which would absorb all visible wavelengths both from streetlights and the sun. While this would reduce light pollution, it would also add to the urban heat island effect and contribute to global warming, and is therefore not as desirable as selective wavelength absorbance. This practice would conflict with LEED and Transportation Research Board efforts to use "cool asphalt pavements."[20]

To complete the proposed work, the LRC partnered with Passonno Paints, a paint manufacturer based in Watervliet, NY to advise on materials and manufacturability.

Methodology

The project team worked with company partner Passonno Paints to attempt to order the three dyes listed in Figure 3. However, Passonno determined that the red-absorbing dye, Patent Blue (with Chemical Abstracts Service, or CAS, identifier 129-17-9), is considered carcinogenic, and could not be ordered due to safety reasons. An alternative dye with absorption in the same portion of the visible spectrum was not identified. The green-absorbing dye under original consideration, Methyl Eosin (CAS 23391-49-3) was not readily available through commercial channels and so instead Passonno procured Eosin Y (CAS 548-26-5), which has a similar peak absorbance wavelength and absorption bandwidth. Passonno purchased the blue-absorbing dye Rosolic Acid (CAS 603-45-2) as originally planned.

The two dyes used, Eosin Y and Rosolic Acid, were selected based on their absorbance characteristics shown in *The Sigma-Aldrich Handbook of Stains, Dyes, and Indicators* by Floyd J. Green.[21] In order to obtain the same absorption characteristics shown in that book, the authors used the information given there about the solvents used to obtain those photometric characteristics. The Eosin Y was mixed into a solvent made of 100 mL distilled water and 1 mL 1% sodium carbonate solution. Three solutions were made with varying concentrations of Eosin Y powder at 0.8 mg, 2.6 mg , and 4.9 mg. The Rosolic Acid was mixed into a solvent made of 100 mL of 200-proof ethanol and 2 mL hydrochloric Acid. Again, three solutions were made with varying concentrations of Rosolic Acid powder: 0.6 mg, 2.3 mg, and 4.1 mg. The lowest concentration of Eosin Y was close to (15% higher than) the concentration given in the *Sigma-Aldrich Handbook*, but the lowest concentration of Rosolic Acid was 2.4 times greater than called for in the *Handbook* due to limitations in material handling capabilities. After mixing, the six dyes were put into glass test tubes with rubber stoppers.

Liquid Dyes

To measure the dyes' spectral transmittances in liquid form, part of each solution was transferred into an empty clear plastic cuvette (small rectangular test tubes), with a square cross section of 1 cm x 1 cm. Each cuvette was placed in front of a tungsten halogen light source and the light spectrum transmitted through the cuvette was recorded from 380 nm to 830 nm at 2 nm increments by a monochromator/ spectrograph (Princeton Instruments, Acton Spectra Pro 2300i). The measurements were performed in an otherwise dark laboratory with black walls. The software provided by Princeton Instruments recorded the transmitted radiance of 1) an empty cuvette, and 2) each individual dye filled cuvette. Using this information it was possible to calculate each dye solution's relative transmittance curve from 380 nm to 830 nm at 2 nm increments.

An analog of absorption was calculated as

$$\text{Absorbance}_{\lambda} = -\log(\text{Radiance}_{\text{dye},\ \lambda} / \text{Radiance}_{\text{empty cuvette},\ \lambda})$$

Coated Surface

One concern about using these dyes as a coating for roadways is whether their optical properties change when they are used to coat a surface. To investigate this, the optical performance of the dye mixtures was tested on a surface to simulate a roadway. Six days after the dyes were mixed, approximately 1 to 2 mL of two dyes, the 0.8 mg concentration of Eosin Y and the 0.6 mg concentration of Rosolic Acid, were dropped onto the glossy white section and the matte white section of a drawdown card used by the coating material industry (BYK product PA-2818). Each drop of dye mixture coated the card in a spot several centimeters in diameter. The coated cards were allowed to dry for two days. These samples were illuminated by a tungsten halogen light source (in the presence of fluorescent ambient lighting), and the spectral power distribution of the reflected light was measured on the sample surface by a spectroradiometer (Photo Research, Spectra Scan PR740) from 380 nm to 780 nm in 1 nm increments for both the dye-coated areas and blank cards. The measurements were recorded by a LabView program for 1) Eosin Y on matte white and 2) on glossy white, for 3) Rosolic Acid on matte white and 4) on glossy white, and for a condition without applied dye for 5) matte white and 6) glossy white. An analog of the absorption was calculated as

$$\text{Absorbance}_{\lambda} = -\log(\text{Radiance}_{\text{dye},\ \lambda} / \text{Radiance}_{\text{blank card},\ \lambda})$$

Effect of Dye Aging

Another concern about using these dyes as a roadway surface coating is whether their optical performance changes over time. To test this, the measurements described above for the liquid dyes were conducted twice, first on the day the dyes were mixed and again two months later, in order to determine how absorbance changes over time. During the intervening two months, the dyes were stored inside an opaque cabinet in test tubes with rubber stoppers. Also, the dyes were photographed one month after mixing.

Effect on Pavement Reflectance

As discussed below, the dyes largely lost their ability to absorb certain wavelengths preferentially when coating a surface directly. Therefore, a mathematical simulation was performed to assess the effect of the dyes on pavement assuming that their absorption properties as a liquid are maintained (e.g., if a suitable encapsulation method were developed). This was calculated as:

$$\text{Reflected Light}_\lambda = \text{Asphalt reflectance}_\lambda \times \text{Relative Dye Transmittance}_\lambda \times \text{Source Radiance}_\lambda \times V_\lambda$$

where V_λ is the photopic luminous efficiency function, which converts units of energy (radiant power in watts) into units of light (lumens).

Results

Liquid Dyes

Figure 4 shows the relative spectral absorbance of the liquid Eosin Y dye mixtures. Of the three concentrations, the 0.8 mg formulation has the narrowest absorbance band and has a peak relative absorbance at 516 nm, which is close to the peak absorbance of 514 nm reported in the *Sigma Aldrich Handbook*. The 0.8mg formulation is the closest to the concentration reported in the *Handbook*. Human color vision perceives light at 514 or 516 nm as a green color.

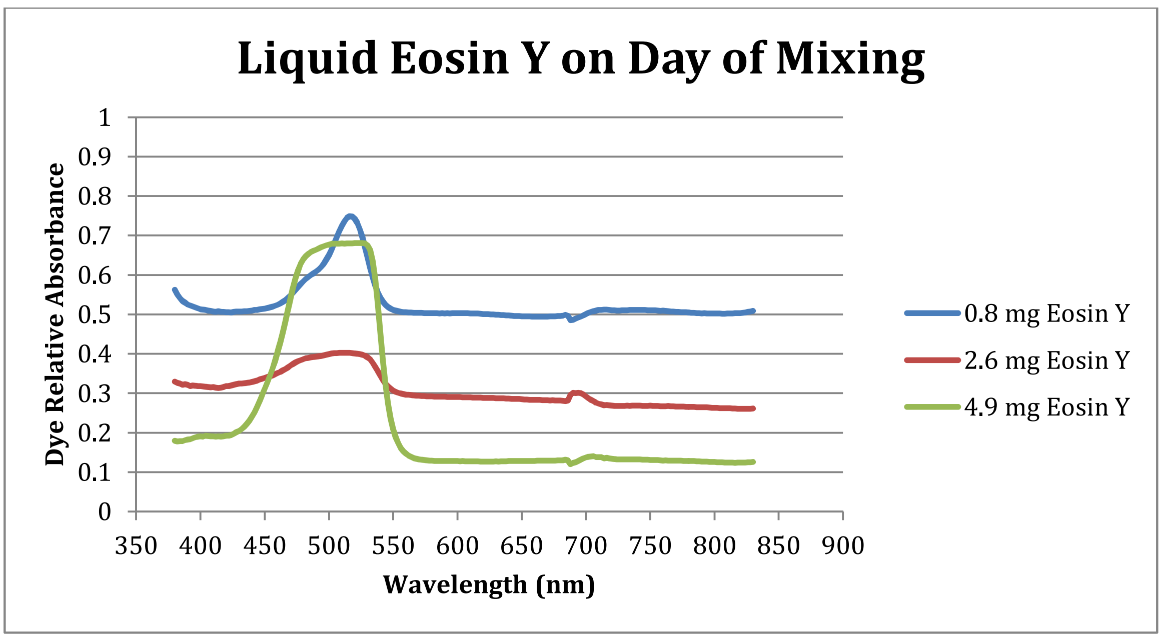


Figure 4: Eosin Y liquid dye relative absorbance. Measurements made the same day that the solid dye was mixed with solvent.

Figure 5 shows the relative spectral absorbance of the liquid Rosolic Acid dye mixtures. Of the three Rosolic Acid concentrations, the 0.6 mg formulation has the narrowest absorbance range and shows a peak absorbance at 484 nm, which is close to the 482 nm peak absorbance reported in the *Sigma Aldrich Handbook*. This formulation is the closest to the concentration reported in the *Handbook*. Human color vision perceives light at 482 or 484 nm as a blue color.

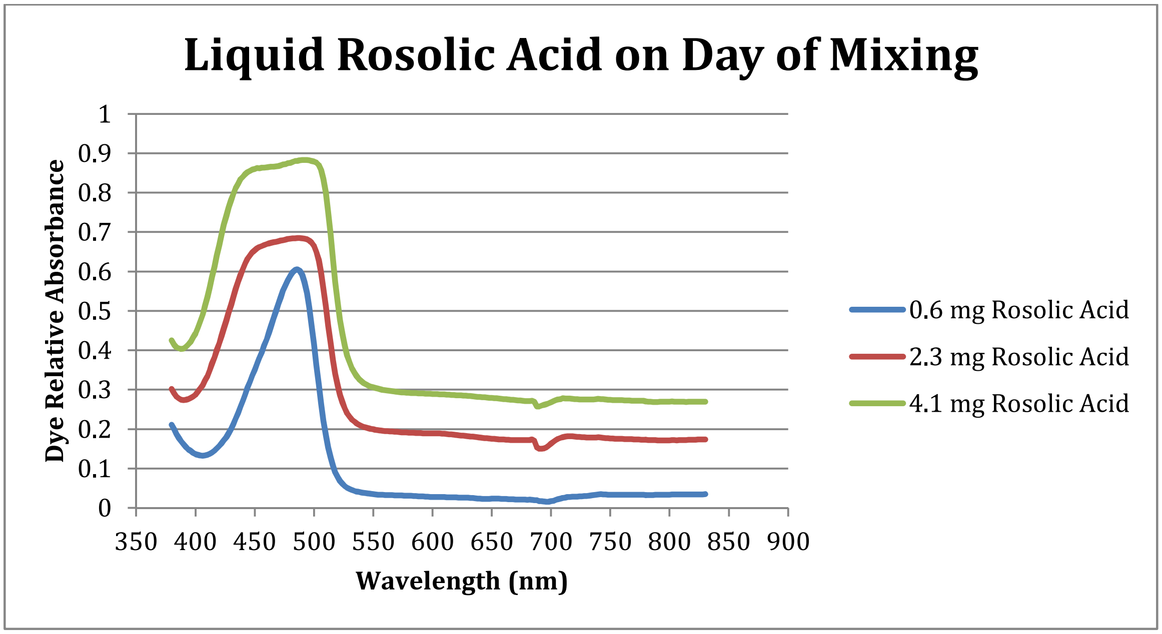


Figure 5: Rosolic acid liquid dye relative absorbance. Measurements made the same day that the solid dye was mixed with solvent.

Coated Surface

Figure 6 shows the absorbance of the dyes after they have been used to coat matte and glossy card stock and allowed to dry. The Rosolic Acid coatings did not appear to absorb light preferentially at any particular wavelength. The Eosin Y coating did preferentially absorb some light, but the amount of absorption was small and the peak wavelength shifted from 516 nm for the liquid dye to 533 nm for the coated dye. Further, the effect was more pronounced for the glossy card stock.

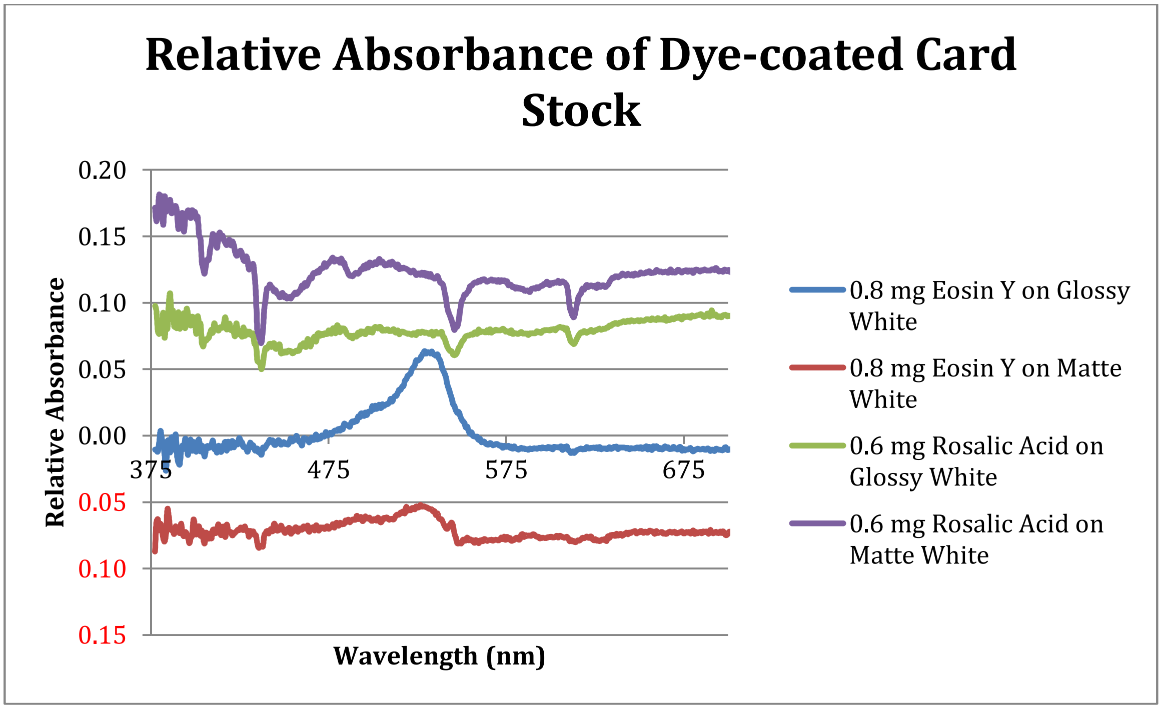


Figure 6: Relative absorbance of dye-coated card stock. Coatings and measurements were made 6 days after dye mixtures were fabricated.

Figure 7 shows photographs of card stock coated with the Eosin Y 0.8 mg formulation under white, blue, and green light. As suggested by Figure 6, the glossy card stock shows a slight amount of increased absorbance under green light compared with other wavelengths of light.

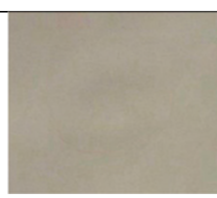
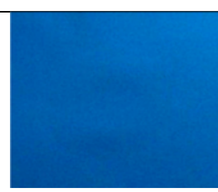
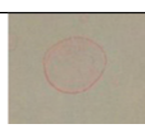
	White light (fluorescent)	Blue light (LED with 480 nm peak)	Green Light (LED with 530 nm peak)
Matte White Card Stock			
Glossy White Card Stock			

Figure 7: Photographs of card stock coated with Eosin Y under white, blue, and green light. Note the slightly darker circle of the glossy white card stock under green light.

Figure 8 shows photographs of card stock coated with the Rosolic Acid 0.6 mg formulation under white, blue, and green light. As suggested by Figure 6, the card stock does not show any preferential absorbance of any particular wavelength of light.

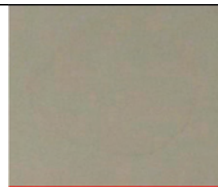
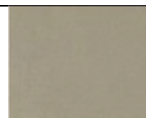
	White light (fluorescent)	Blue light (LED with 480 nm peak)	Green Light (LED with 530 nm peak)
Matte White Card Stock			
Glossy White Card Stock			

Figure 8: Photographs of card stock coated with Rosolic Acid under white, blue, and green light.

Effect of Aging

As shown in Figure 9, after two months of aging the relative absorbance of the Eosin Y 2.6 mg and 4.9 mg formulations increased in strength. The selectivity of the absorbance also appears to have increased for all three formulations.

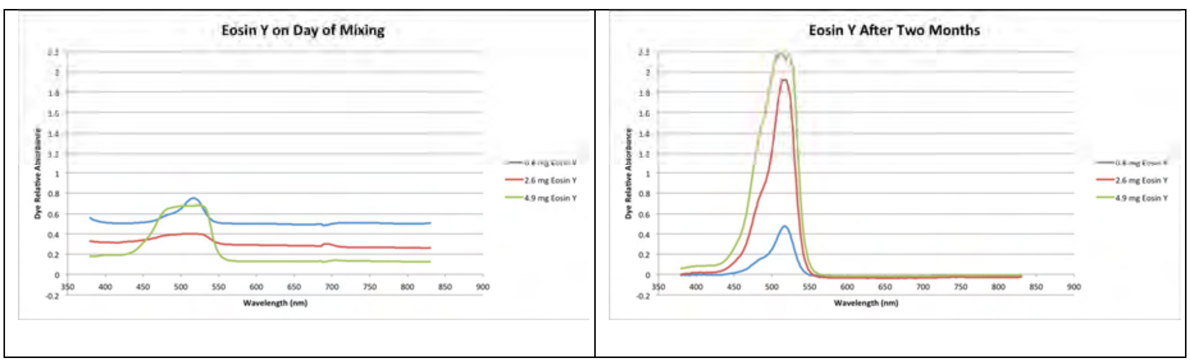


Figure 9: Relative absorbance of liquid Eosin Y on day of mixing and two months after mixing.

As illustrated in Figure 10, the Eosin Y liquid dye does preferentially absorb green wavelengths of light. The “1 mg,” “2 mg,” and “4 mg” annotations in the photographs are approximations of the 0.8 mg, 2.6 mg, and 4.9 mg formulations of the dye mixtures. (There is also an increase absorption of blue light at 480 nm, which is suggested by the data in Figure 9.)

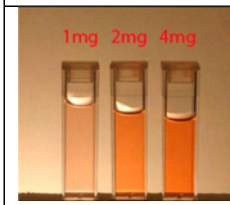
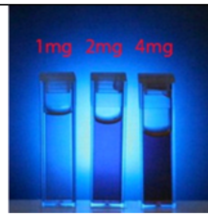
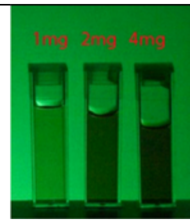
White light (halogen)	Blue light (LED with 480 nm peak)	Green Light (LED with 530 nm peak)
		

Figure 10: Photographs of cuvettes filled with Eosin Y liquid dyes illuminated by white, blue, and green light. The photographs were taken one month after the dyes were mixed. Note the dark appearance of the "2 mg" formulation under green light in comparison with white and blue light.

As shown in Figure 11, after two months of aging the relative absorbance of the Rosolic Acid decreased, and the spectral selectivity decreased too.

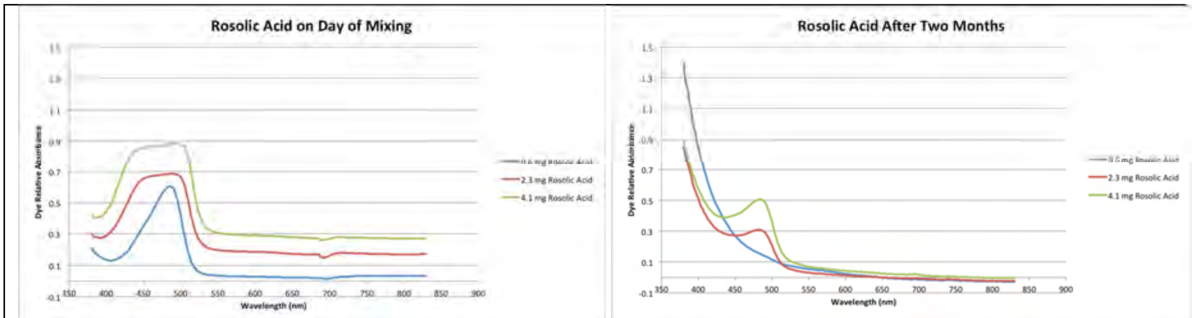


Figure 11: Relative absorbance of liquid Rosolic Acid on day of mixing and two months after mixing.

As illustrated in Figure 12, the Rosolic Acid liquid still preferentially absorbs blue wavelengths of light despite the passage of time. The "1 mg," "2 mg," and "4 mg" annotations in the photographs are approximations of the 0.6 mg, 2.3 mg, and 4.1 mg formulations of the dye mixtures.

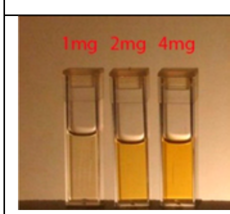
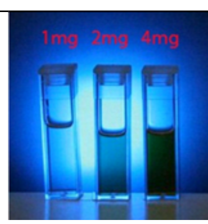
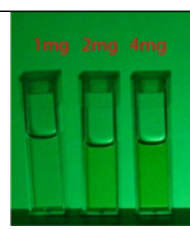
White light (halogen)	Blue light (LED with 480 nm peak)	Green Light (LED with 530 nm peak)
		

Figure 12: Photographs of cuvettes filled with Rosolic liquid dyes illuminated by white, blue, and green light. The photographs were taken one month after the dyes were mixed.

Effect on Pavement Reflectance

In order to estimate the impact of the dyes on the ability of roadway pavement material to reflect light, the spectral power distributions (SPDs) of an incandescent (white) light source and of blue (peak wavelength 480 nm) and green (peak wavelength 530 nm) LEDs were measured. Relative SPDs for these sources are shown in Figure 13. Also shown in Figure 13 are the spectral reflectance of asphalt pavement,[24] as well as a mathematical simulation of asphalt filtered by liquid forms (in a suitable encapsulant) of Rosolic Acid (4.1 mg concentration on day of mixing) or Eosin Y (4.9 mg concentration two months after mixing).

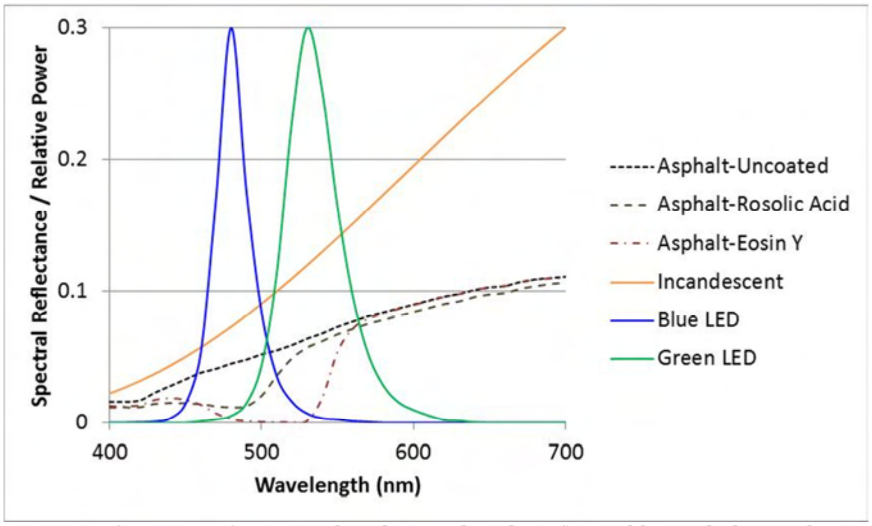


Figure 13: Spectral reflectance of untreated asphalt and asphalt filtered by each dye, and relative spectral power distributions of incandescent, blue LED and green LED sources.

The overall pavement reflectance of the untreated asphalt pavement under the incandescent light source is 8.0%. When coated with Rosolic Acid in liquid form, the asphalt's reflectance under incandescent lighting is 7.2%, a reduction in reflectance of 9% from the uncoated asphalt. When coated with Eosin Y in liquid form, the asphalt's reflectance is 6.3%, a reduction of 21% from uncoated asphalt.

In comparison, the Rosolic Acid coating reduced the reflectance of the asphalt by 55% under the blue LED light source, while reducing the reflectance by only 12% under the green LED light source.

The Eosin Y coating reduced the reflectance of the asphalt by 82% under the blue LED light source and by 61% under the green light source. Inspection of Figure 13 shows that the absorption of light by the Eosin Y dye (when the transmittance of light is less than 10%) covers a rather broad range of wavelengths from 480 to 530 nm, and at the concentration used to develop this figure it attenuates the transmission of both blue and green light. This absorption is qualitatively evident from Figure 10, which shows the relative darkness of the Eosin Y solutions for both blue and green illumination.

The measurement data suggest that treating asphalt pavement with dyes such as Rosolic Acid and Eosin Y, in the concentrations used in the calculations underlying Figure 13, would have relatively modest (9%-21%) reductions in the reflectance of asphalt pavement by broadband white light sources such as incandescent or halogen light sources used in vehicle headlamps, but would sharply reduce (55%-82%) the reflectance for narrowband sources such as blue or green LEDs.

Figure 13 shows a calculation of the relative spectral reflectance of daylight reflected off of a pavement surface with and without a dye composed of both the Rosolic Acid and Eosin Y dyes. This calculation assumes that the dyes are encapsulated so as to retain their optical properties as liquid dyes and that their absorbances are additive. Considering the light over all wavelengths in the visible range, the untreated pavement surface reflects 66% of the incident daylight, while the treated pavement reflects 42%, indicating a 36% reduction in reflectance.

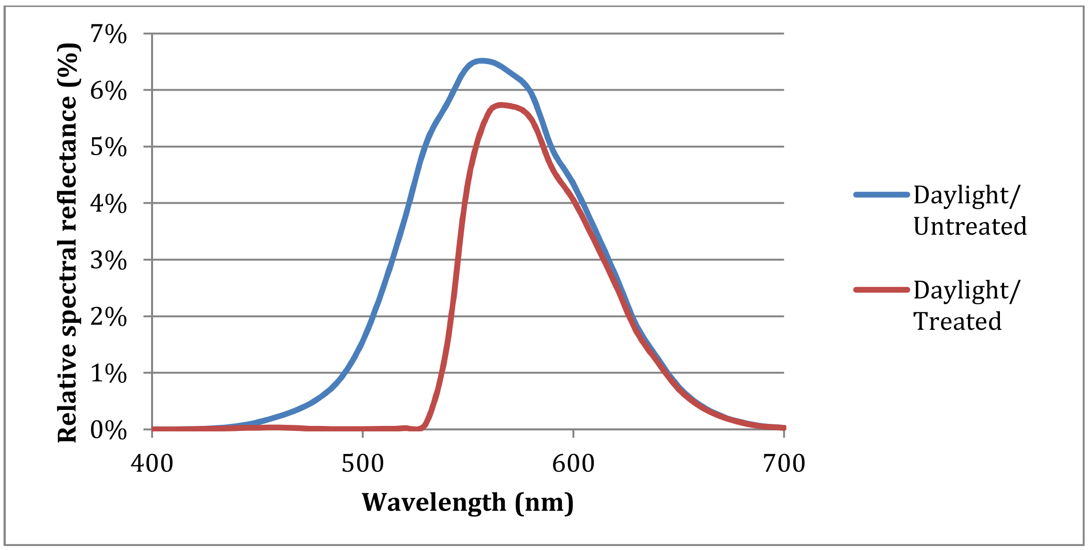


Figure 13: Calculation of relative spectral reflectance of daylight on pavement untreated and treated with both Rosolic Acid and Eosin Y dyes.

Figure 14 shows a calculation of the relative spectral reflectance of light from a simulated streetlight with blue and green LEDs reflected off of a pavement surface with and without a dye composed of both the Rosolic Acid and Eosin Y dyes. The untreated pavement surface reflects 27% of the incident light from the fixture, while the treated pavement reflects 9%, indicating a 67% reduction in reflectance. Further investigation would be needed to assess the effect of adding a red LED to the streetlight and a red-absorbing dye to the roadway coating.

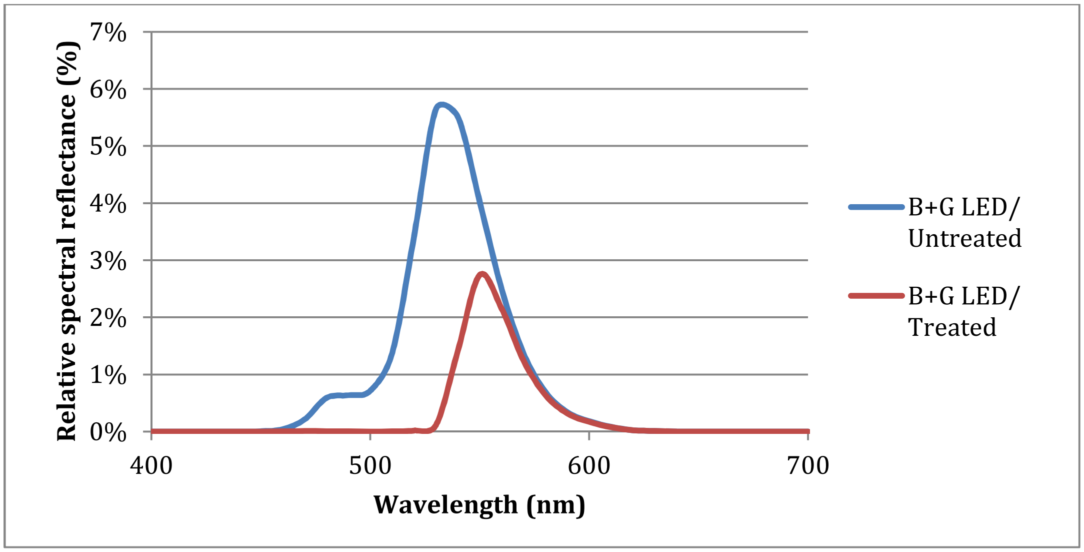


Figure 14: Calculation of relative spectral reflectance of blue and green LEDs on pavement untreated and treated with both Rosolic Acid and Eosin Y dyes.

Since roadway hazards such as pedestrians are three-dimensional objects which receive substantially more light on their vertical surfaces from headlamps than they do from overhead lighting, the reduction in pavement reflectance associated with narrowband overhead illumination coupled with selectively-absorbing dye pavement treatments would have the net effect of increasing contrast of such objects. In turn, this would be expected to improve visual performance.[25]

Discussion and Conclusion

The goal for exploring this concept was to develop a roadway coating that would largely maintain the reflective properties of a roadway (so as not to increase the metropolitan heat island effect or global warming) but would absorb much of the light from a custom-made LED streetlight that relies on metamerism to produce white light from colored LEDs. The authors were able to mix liquid dyes that preferentially absorbed blue and green light. A mathematical simulation of a roadway coated with these dyes while maintaining their optical properties in the liquid state would result in a 36% reduction in reflectance of daylight but a 67% reduction in light from a simulated LED streetlight. Potentially, these could form a basis for an RGB roadway coating and streetlight system to reduce sky glow light pollution.

However, a number of hurdles still stand in the way of such a system:

1. Red light absorbance. Due to safety policies, the original red-light-absorbing dye was not procured for this study, and an alternative was not identified. The results above include only blue and green light. To produce white light, the streetlight fixture would need to incorporate red too, and so a corresponding dye would be needed.
2. Encapsulation. The dyes would need to coat a roadway surface in order to prevent sky glow. When the two dyes studied here were used to coat a card stock surface, their wavelength-selective optical properties were substantially reduced. Therefore, further development efforts would be needed to identify means of coating a surface while preserving optical properties. For example, it may be possible to embed the dyes in a substrate such as acrylic, which has good weather resistance and color retention properties.[22] Another potential method would be to contain the liquid dye within clear polymer spheres.
3. Effect of Aging. The experiment done here showed that the optical properties of the dyes changed significantly after only one to two months, even though the dyes were stored in a dark space. Changes may occur even more quickly if the dyes had been exposed to ambient light during this time as would occur for a roadway surface. A roadway coating would need to remain stable for years.
4. Environmental Effects. One of the dyes proposed for this study could not be obtained due to human health concerns. Any dye used to coat a roadway surface would need to be benign to human health and the environment.
5. Driving Safety. The experiment showed that the dyes would need to be encapsulated or otherwise protected to use as a roadway surface coating. Whatever material is used would need to maintain the driving safety properties of the roadway. For example, a polymer matrix might make the road more slippery.

6. Cost. Eosin Y costs approximately $150 per kg and Rosolic Acid costs approximately $2,500 per kg from a commercial supplier.[23] While these prices would likely be reduced for bulk purchases, they are likely to remain expensive for a roadway coating.

In conclusion, the concept of a streetlight using multiple narrow band output to create white light, in conjunction with a roadway surface coating system composed of spectrally selective absorptive dyes, in order to reduce sky glow light pollution is theoretically possible. However, the concept still faces many significant challenges, particularly related to the specific encapsulation of the dye material and its stability. Because of these challenges, the proposed concept is not practical for short term implementation.

Acknowledgements

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