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Image-Based Remote Measurement of Retro-Reflectivity of Roadways Assets in the Daytime

Vahid Balali, PhD





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IMAGE-BASED REMOTE MEASUREMENT OF RETRO-REFLECTIVITY OF ROADWAYS ASSETS IN THE DAYTIME

Vahid Balali, PhD

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| 16 | 16. Abstract One of the most effective and low-cost ways for improving nighttime driving safety of transportation systems is maintaining the traffic signs retro-reflectivity. The U.S. Federal Highway Administration (FHWA) has enacted new rules on the minimum level of retroreflectivity which compels agencies to measure the current levels of retro-reflectivity of traffic signs and develop plans for replacing or improving their condition. Current practices in assessing and measuring the retro-reflectivity of traffic signs, including handheld retroreflectometer and mobile technologies, are financially and practically infeasible because of their physical and technical constraints. This research project explores and presents the possibility of an inexpensive, safe, and cost-effective computer vision method for remotely measuring the retro-reflectivity of traffic signs during daytime using High Dynamic Range (HDR) images. By capturing two images simultaneously during the daytime, the method simulates nighttime visibility for each sign and measures retro-reflectivity at a level of accuracy that is mandated by FHWA guidelines. The research project develops a remote retro-reflecto-meter that consists of a consumer-grade camera, flashlight, GPS receiver, and screen. An experimental test was conducted on different types of traffic signs with different levels of retro-reflectivity which are located at different distances in real-world conditions to validate the performance of the method. The results, compared with data collected from a standard retro-reflectometer, demonstrates the potential of the method in lowering costs, improving safety, perform during the daytime, and shorten time required for retro-reflectivity data collection. | | | |
| | The proposed technique is faster, cheap manual sign inspection, particularly for carry around and measure retro-reflectiv a vehicle to be used by an inspector in replace/repair defective signs and mart If CalTrans wants to implement the de CalTrans' current vendors which aim to | ber, and safer compared to the state-of-the-ard overhanging signs which are hard to reach. The vity levels during the daytime on foot. The techn the passenger seat. This study will provide a kings while avoiding expensive retro-reflecto- eveloped technology at a larger-scale, their provide mobile asset management services t | as neither requires nig e developed technique nique can be mounted to n effective way for Cal meters and nighttime research team will see o transfer the develope | httime operation nor allows inspectors to o and detached from Trans to inspect and visibility inspections. k opportunities with ed technology. |
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TABLE OF CONTENTS

| Executive Summary | 1 |
|--|----|
| I. Introduction | 2 |
| II. Related Work | 7 |
| III. Method | 11 |
| Camera Exposure Calibration | 12 |
| Retro-Reflectivity Measurement | 16 |
| IV. Experimental Results and Discussions | 19 |
| Data Collection and Setup | 19 |
| Performance Evaluation | 20 |
| Results | 21 |
| Discussion | 24 |
| V. Conclusion | 25 |
| Abbreviations and Acronyms | 26 |
| Bibliography | 27 |
| About the Author | |
| Peer Review | 32 |

LIST OF FIGURES

| 1. | Some Examples of Daytime (Left) and Nighttime (Right) View of Traffic Signs | 3 |
|-----|---|----|
| 2. | Retro-Reflectivity Maintenance Methods | 5 |
| 3. | Advanced Mobile Asset Collection (AMAC) | 8 |
| 4. | Method Overview for Image-Based Retro-Reflectivity Measurement during Daytime | 11 |
| 5. | (a) Image with Flash; (b) Image without Flash; (c) Night Photo Reconstruction | 12 |
| 6. | Creating HDR Images from LDR Images | 13 |
| 7. | Misalignment Produces a Significant Artifact around the Edges of Objects | 14 |
| 8. | Cross-Correlation Between the Edges of $I_{_{Day}}$ and $I_{_{Flash+Day}}$ | 15 |
| 9. | (a) Before Sub-Pixel Alignment; (b) After Sub-Pixel Alignment | 16 |
| 10. | Component of Retro-Reflectivity | 16 |
| 11. | Camera Setup for Data Collection at Different Times of Day and at Different Distances | 19 |
| 12. | An HDR Photograph of a Spherical Mirror at Six Different Exposure Time | 19 |
| 13. | Response Curve for Different Color Channels | 20 |
| 14. | Reconstructing Nighttime Images from Images Taken in the Daytime | 21 |
| 15. | Impact of Time on Image-Based Retro-Reflectivity Measurement for Different Types of Traffic Signs at Different Distances | 22 |
| 16. | Impact of Distance on Image-Based Retro-Reflectivity Measurement for Different Types of Traffic Signs at Different Times | 23 |

LIST OF TABLES

| 1. | Minimum Retro-reflectivity Levels from the MUTCD. Retro-Reflectivity Levels Are Measured in at an Observation Angle of 0.2° and an Entrance Angle of -4.0° | 4 |
|----|--|----|
| 2. | Camera Setting for Data Collection | 20 |
| 3. | Results of Ground Truth | 20 |
| 4. | Performance of Proposed Method | 24 |

EXECUTIVE SUMMARY

One of the most effective and low-cost ways for improving nighttime driving safety of transportation systems is maintaining the traffic signs retro-reflectivity. The U.S. Federal Highway Administration (FHWA) has enacted new rules on the minimum level of retro-reflectivity which compels agencies to measure the current levels of retro-reflectivity of traffic signs and develop plans for replacing or improving their condition. Current practices in assessing and measuring the retro-reflectivity of traffic signs, including handheld retro-reflectometer and mobile technologies, are financially and practically infeasible because of their physical and technical constraints.

This research project explores and presents the possibility of an inexpensive, safe, and cost-effective computer vision method for remotely measuring the retro-reflectivity of traffic signs during daytime using High Dynamic Range (HDR) images. By capturing two images simultaneously during the daytime, the method simulates nighttime visibility for each sign and measures retro-reflectivity at a level of accuracy that is mandated by FHWA guidelines. The research project develops a remote retro-reflecto-meter that consists of a consumer-grade camera, flashlight, GPS receiver, and screen. An experimental test was conducted on different types of traffic signs with different levels of retro-reflectivity which are located at different distances in real-world conditions to validate the performance of the method. The results, compared with data collected from a standard retro-reflectometer, demonstrates the potential of the method in lowering costs, improving safety, perform during the daytime, and shorten time required for retro-reflectivity data collection.

The proposed technique is faster, cheaper, and safer compared to the state-of-the-art as neither requires nighttime operation nor manual sign inspection, particularly for overhanging signs which are hard to reach. The developed technique allows inspectors to carry around and measure retro-reflectivity levels during the daytime on foot. The technique can be mounted to and detached from a vehicle to be used by an inspector in the passenger seat. This study will provide an effective way for CalTrans to inspect and replace/repair defective signs and markings while avoiding expensive retro-reflecto-meters and nighttime visibility inspections. If CalTrans wants to implement the developed technology at a larger-scale, their research team will seek opportunities with CalTrans' current vendors which aim to provide mobile asset management services to transfer the developed technology.

I. INTRODUCTION

Roadway assets are essential physical components of an infrastructure system that require preventive, restorative, or replacement work activities to preserve their functionality in an acceptable level of service. Managing and maintaining infrastructure is not a new problem. In recent decades, however, significant expansion in size and complexity of the infrastructure networks have posed several new engineering and management problems on how existing infrastructure can be monitored, prioritized, and maintained in a timely fashion.¹ Fast paced deterioration coupled with limited funding have motivated the California Departments of Transportation (CalTrans) to consider prioritizing roadway assets based on their existing conditions. In the meantime, the American Society of Civil Engineers (ASCE) has estimated that \$170 billion in capital investment are needed on an annual basis to improve existing conditions of the national infrastructure system.² Despite its significance, there is a lack of reliable and up-to-date database which can integrate geospatial, economic, and maintenance asset data. Such centralized databases can help CalTrans better prioritize different roadway sections for maintenance and replacement planning purposes. This requires the CalTrans to always keep an updated record on the condition of many types of roadway assets such as light poles, guardrails, pavement markings, and traffic signs.³

The first step in managing these assets requires monitoring their as-is conditions which involve evaluating placement, message clarity, line-of-sight, redundancy, daytime color, and nighttime visibility. Nighttime visibility depends on a material property called retro-reflectivity. Retro-reflectivity is a property of surface materials that reflects light transmitted by a distant source.⁴ Retro-reflective materials are commonly used for traffic signs to enhance their visibility during the night. A perfect retro-reflector, however, reflects the incoming light back towards the headlight and can cause a safety hazard for drivers. To create optimum visibility and to divert the reflected light from the driver's direct line of sight, signs are coated with certain matt sheeting materials that have prismatic and micro-prismatic patterns. This coating mechanism allows signs to be located safely out of the incoming light's line of travel and yet be visible to the drivers at night. Figure 1 illustrates the role of retro-reflective material in sign visibility.

¹ Golparvar-Fard, Balali, and de la Garza, "Segmentation and Recognition of Highway Assets Using Image-Based 3D Point Clouds and Semantic Texton Forests."

² ASCE, "National Infrastructure Report Card."

³ Balali, Ashouri Rad, and Golparvar-Fard, "Detection, Classification, and Mapping of U.S. Traffic Signs Using Google Street View Images for Roadway Inventory Management"; Cheok et al., "Assessing Technology Gaps for the Federal Highway Administration Digital Highway Measurement Program."

⁴ Austin and Schultz, Guide to Retroreflection Safety Principles and Retrorereflective [Sic] Measurements.



Figure 1. Some Examples of Daytime (Left) and Nighttime (Right) View of Traffic Signs

The U.S. Federal Highway Administration (FHWA) expects that improvements to nighttime visibility of traffic signs will help drivers better navigate the roads and thus promote safety and mobility. Such improvement is one of the six effective low-cost safety improvements for roadways.⁵ Traffic sign retro-reflectivity condition is one of the most critical factors for nighttime driving safety. Due to the significance of nighttime performance for traffic signs, the new traffic signs minimum retro-reflectivity standard issued by the⁶ has compelled transportation agencies to evaluate how to comply under stringent budget situations and timeframes. Since January 2012, all agencies must establish and implement a sign maintenance program which addresses the minimum sign retro-reflectivity requirements. Since January 2015, all agencies must comply with the new retro-reflectivity requirements for all red and white "regulatory" signs (such as Stop and Speed Limit signs), yellow "warning" signs, and green/white "guide" signs. As of January 2018, moreover, new retroreflectivity requirements will also be enforced for overhead guide signs and all street name signs.⁷ Addressing the minimum sign retro-reflectivity requirements, agencies first measure the current levels of retro-reflectivity and proceed to devise plans for replacing or improving the condition of those assets which do not meet the minimum level of service.

According to the FHWA's Manual on Uniform Traffic Control Devices (MUTCD),⁸ a minimum retro-reflectivity requirement depends on the color combination of a sign (Table 1). These guidelines require retro-reflectivity to be measured in at an observation angle of 0.2° and an entrance angle of 4.0°. Here is candela, the unit of luminous intensity, which is the power that is emitted by the light source in a particular direction (brightness of a display devices); is the unit of illuminance, which is a measure of how much the incident light illuminates the surface (hits and passes through a surface).

⁵ Molino et al., "Simulator Evaluation of Low-Cost Safety Improvements on Rural Two-Lane Undivided Roads: Nighttime Delineation for Curves and Traffic Calming for Small Towns"; Pour-Rouholamin and Zhou, "Analysis of Driver Injury Severity in Wrong-Way Driving Crashes on Controlled-Access Highways."

⁶ FHWA, Manual on Uniform Traffic Control Devices for Streets and Highways.

⁷ Carlson and Picha, "Sign Retroreflectivity Guidebook."

⁸ FHWA, Manual on Uniform Traffic Control Devices for Streets and Highways.

| Sheeting Type (ASTM D4956-04) | | | | | |
|-------------------------------|---------------------|-----------------|----------------|-------------------------------|---------------------|
| | | Beaded Sheeting | | Prismatic Sheeting | _ |
| Sign Color | I | II | III | III, IV, VI, VII, VIII, IX, X | Additional Criteria |
| White on Green | W*; G≥7 | W*; G≥15 | W*; G≥25 | W≥250; G≥25 | Overhead |
| | W*; G≥7 W≥120; G≥15 | | Ground-mounted | | |
| Black on Yellow | Y*; O* | Y≥50; O≥50 | | | |
| Black on Orange | Y*; O* | O* Y≥75; O≥75 | | | |
| White on Red | | | | | _ |
| Black on White | | W≥50 | | | |

Table 1.Minimum Retro-reflectivity Levels from the MUTCD. Retro-Reflectivity
Levels Are Measured in at an Observation Angle of 0.2° and an Entrance
Angle of -4.0°

Nighttime visibility traffic signs are difficult to assess with visual inspection methods during the daytime. The retro-reflective properties of all sign sheeting materials degrade over time making signs progressively less visible at night. Environmental conditions, such as UV-radiation from the sun, moisture, and pollutants cause a substantial amount of the deterioration in retro-reflectivity performance.⁹ However, loss of retro-reflectivity can also occur due to vandalism, such as paint ball shots, gunshots, and spray paint.¹⁰ Given that current practices for traffic sign retro-reflectivity assessments are still performed manually, this has proven to be time-consuming, unsafe, and expensive. Existing mobile methods are also expensive and have to be performed during nighttime.

The latest MUTCD recommends two approaches for managing retro-reflectivity (Figure 2). **Management methods** are primarily based on life expectancy of the overall sign inventory. With these methods in mind, life expectancy is estimated based on a number of factors, including warranties, demonstrated performance, and/or control sign assessments. **Assessment methods** involve regular nighttime visibility measurements. The MUTCD permits the combination of these methods in any responsible program that reasonably assures compliance.

⁹ Ai and Tsai, "An Automated Sign Retroreflectivity Condition Evaluation Methodology Using Mobile LIDAR and Computer Vision"; Jalayer et al., "Evaluation of Remote Sensing Technologies for Collecting Roadside Feature Data to Support Highway Safety Manual Implementation"; Khalilikhah, Heaslip, and Song, "Can Daytime Digital Imaging Be Used for Traffic Sign Retroreflectivity Compliance?"; Balali and Golparvar-Fard, "Evaluation of Multiclass Traffic Sign Detection and Classification Methods for US Roadway Asset Inventory Management."

¹⁰ Khalilikhah, Heaslip, and Louisell, "Analysis of the Effects of Coarse Particulate Matter (PM10) on Traffic Sign Retroreflectivity"; Khalilikhah, Heaslip, and Hancock, "Traffic Sign Vandalism and Demographics of Local Population: A Case Study in Utah."



Figure 2. Retro-Reflectivity Maintenance Methods

There are several commonly used management methods, some of which are noted below.

Expected Sign Life Method – Using various measures of demonstrated sheeting life, signs are replaced when they reach a certain age. This method requires agencies to track the installation dates using stickers on the back of the signs, bar codes, or computerized sign management systems. However, manually inspecting these stickers or barcodes can be very time-consuming, especially if the stickers or barcodes are not easily visible on the sign.

Blanket Replacement Method is similar to the expected sign life method, except that individual signs are not tracked. Instead, a group of signs are replaced at the same time based on the location and/or the type of signs. In this method, as shown in Figure 2, an agency divides their jurisdiction into corridors and/or zones where the number of areas are related to replacement cycles. All signs are then replaced in each zone/corridor according to their replacement cycles.

In **Control Signs Method**, for a group of similar signs, a single representative sign is placed at a controlled location. The control sign is periodically measured for retro-reflectivity. When the control sign is near minimum retro-reflectivity requirement, its in-service companions are replaced. This method has a low cost and does not require labor-intensive processes. However, a large set of control signs and adequate space are required to create statistically significant results.

For management-based methods, signs are assigned a life expectancy when they are first installed. Their degradation speeds, however, vary based on their location and a geography's environmental conditions. Having management methods replace signs will result in higher sign functionality.

Compared to management methods, assessment methods lead to less frequent sign replacements and improve efficiency. These methods could be performed through visual inspection during nighttime (**Nighttime Visual Inspection Method**) or by using retro-reflectometer devices during the daytime (**Retro-reflectivity Measurement Method**). Through these methods, retro-reflectivity could be measured more regularly, and recommendations can be provided on the best timing for replacing a sign based on degradation levels. Manual visual inspections involve some degree of subjectivity, yet research has shown that trained observers can reasonably identify signs with marginal retro-reflectivity.¹¹ Measuring sign retro-reflectivity through a systematic process provides the most direct means of monitoring maintained retro-reflectivity levels and removes subjectivity.

Enforcing these regulations requires agencies to frequently measure current levels of retro-reflectivity and devise replacement plans. Two major measurement techniques are commonly used today: (a) using remote retro-reflectivity measurement devices mounted on inspection vehicles. This device automatically measures retro-reflectivity, though the process ought to be completed during nighttime; (b) a practitioner using a hand-held device to measure retro-reflectivity. This device must physically touch the sign which requires the practitioner to perform this operation manually and sign-by-sign. This process can be performed during the daytime, however, it is time-consuming, unsafe, and expensive.¹² To address current limitations with respect to measurement techniques, a new technique has been developed to (a) perform remote measurements and (b) be used during daytime. More precisely, various computer vision techniques are applied to reconstruct nighttime images using images taken during the day. The reconstructed night images are then used to measure retro-reflectivity which perform remote measurements.

¹¹ Carlson and Lupes, "Methods for Maintaining Traffic Sign Retroreflectivity."

¹² Balali and Golparvar-Fard, "Evaluation of Multiclass Traffic Sign Detection and Classification Methods for US Roadway Asset Inventory Management"; Khalilikhah, Heaslip, and Song, "Can Daytime Digital Imaging Be Used for Traffic Sign Retroreflectivity Compliance?"

II. RELATED WORK

Currently, the most objective method to measure retro-reflectivity is to use handheld retro-reflectometers.¹³ A single handheld retro-reflectometer costs over ten thousand dollars.¹⁴ Because this device needs to be in direct contact with a sign surface to take measurements—even for the overhead signs and those ground mounted signs that are out of reach—its application can be labor-intensive, expensive, and potentially unsafe for inspectors.¹⁵ A bigger challenge is that these devices can only take measurements on predefined geometries which are not the best representatives of actual driving geometries.¹⁶ For example, measurements from twisted and leaning signs can result in retro-reflectivity above the minimum levels, while the actual luminance of the sign under nighttime conditions may be lower than the requirements.¹⁷ All of the management or assessment methods, even those that are standardized by,¹⁸ are costly and/or labor intensive.

The most recent mobile retro-reflectivity methods include: **SMARTS** (Sign Management And Retro-reflectivity Tracking System),¹⁹ **AMAC** (Advanced Mobile Asset Collection),²⁰ **MANDLI** (Retro View),²¹ and **VISULISE** (Visual Inspection of Signs and Panels).²² SMARTS was developed by the Naval Research Laboratory for the FHWA. SMARTS includes a xenon flash, a laser range finder, one color camera, and two monochrome cameras. The unit first sets off a flash and takes a digital image. The image is then processed to estimate the retro-reflectivity of signs.²³ This system was an experimental concept and is not available today. AMAC uses artificial vision and an advanced lighting system to locate, collect, and analyze traffic sign data at night. This data includes retro-reflectivity, luminance, position, dimensions, and color. As shown in Figure 3, AMAC integrates high accuracy GPS with an onboard inertial navigation system to locate and process sign data.²⁴

¹³ Brimley, Carlson, and Ye, "Measurement Bias and Reproducibility of In-Service Sign Retroreflectivity Readings Made with Handheld Instruments"; Hummer, Harris, and Rasdorf, "Simulation-Based Evaluation of Traffic Sign Retroreflectivity Maintenance Practices."

¹⁴ Reynolds, "Determining a Strategy for Efficiently Managing Sign Retroreflectivity in New Hampshire."

¹⁵ Preston et al., "Traffic Sign Life Expectancy"; Balali and Golparvar-Fard, "Segmentation and Recognition of Roadway Assets from Car-Mounted Camera Video Streams Using a Scalable Non-Parametric Image Parsing Method."{"id":"ITEM-2", "itemData":("DOI":"10.1016/j.autcon.2014.09.007", "ISSN":"09265805", "abstract":"© 2014 Elsevier B.V. All rights reserved. This paper presents a non-parametric image parsing method for segmentation and recognition of roadway assets such as traffic signs, traffic lights, pavement markings, and guardrails from 2D car-mounted video streams. The method can be easily scaled to thousands of video frames captured during data collection and does not need training. Instead, it retrieves a set of most relevant video frames (e.g. highway vs. secondary road)

¹⁶ Bhalla, Naidu, and Soh, "Influence of Structure-Actuator Interactions and Temperature on Piezoelectric Mechatronic Signatures for NDE"; Babić, Ščukanec, and Fiolić, "Traffic Sign Analysis as a Function of Traffic Safety on Croatian State Road D3"; Hulme et al., "An Asset Management Framework for Addressing the New MUTCD Traffic Sign Retroreflectivity Standards."

¹⁷ Shcukanec, Babic, and Sokol, "Methodology for Measuring Traffic Signs Retroreflection."

¹⁸ FHWA, Manual on Uniform Traffic Control Devices for Streets and Highways.

¹⁹ Smith and Fletcher, "Evaluation of the FHWA's Sign Management and Retroreflectivity Tracking System (SMARTS) Van."

²⁰ Pike and Carlson, "Investigate the Ability to Determine Pavement Marking Retroreflectivity–Evaluate the Advanced Mobile Asset Collection (AMAC) Mobile Pavement Marking Retroreflectivity Measurement System."

²¹ Harris, "Sign Maintenance Strategies for Agencies to Comply with Proposed FHWA Minimum Retroreflectivity Standards"; Li, "Project 08-06 June 2008."

²² Evans et al., "Assessment of Sign Retroreflectivity Compliance for Development of a Management Plan."

²³ Retterath and Laumeyer, System for automated determination of retroreflectivity of road signs and other reflective objects.; Rasdorf et al., "IT Issues for the Management of High-Quantity, Low-Cost Assets."

²⁴ Pike and Carlson, "Investigate the Ability to Determine Pavement Marking Retroreflectivity–Evaluate the Advanced Mobile Asset Collection (AMAC) Mobile Pavement Marking Retroreflectivity Measurement System."

MANDLI continuously fires a high-intensity flash while its grayscale cameras simultaneously capture frames. One low-intensity camera and one high-intensity camera are coupled to cover a wide dynamic range. Flashlights fire infrared light that is invisible to human eyes at a rate of two per second while the vehicle travels at highway speed.²⁵ VISULISE uses infrared light. It captures reflected light using a stereoscopic system made up of two high-resolution cameras.²⁶ While these methods are practical, their application is costly and require, in some cases, operation at nighttime.



Figure 3. Advanced Mobile Asset Collection (AMAC)

Measuring retro-reflectivity from images taken during the day can address safety concerns. Using image analysis, the entire retro-reflective area of a sign can be measured rather than areas with a 1-inch diameter.²⁷ There are various aspects of an image that cannot be captured through a conventional image. Many of these aspects can be estimated by processing pairs of images taken in carefully adjusted conditions such as image depth, motion, and reflection. Image depth can be estimated using two images that are taken with some disparity.²⁸ Motion can be estimated from two images that are taken from the same location but at different times.²⁹ Reflection can be estimated by analyzing two

²⁵ Harris, "Sign Maintenance Strategies for Agencies to Comply with Proposed FHWA Minimum Retroreflectivity Standards"; Li, "Project 08-06 June 2008."

²⁶ Evans et al., "Assessment of Sign Retroreflectivity Compliance for Development of a Management Plan."

²⁷ Shcukanec, Babic, and Sokol, "Methodology for Measuring Traffic Signs Retroreflection"; Evans, "Development of Assessment Strategies For Sign Retroreflectivity."

²⁸ Lazaros, Sirakoulis, and Gasteratos, "Review of Stereo Vision Algorithms: From Software to Hardware."

²⁹ Horn and G., "Determining Optical Flow"; Balali and Golparvar-Fard, "Segmentation and Recognition of Roadway Assets from Car-Mounted Camera Video Streams Using a Scalable Non-Parametric Image Parsing Method."traffic lights, pavement markings, and guardrails from 2D car-mounted video streams. The method can be easily scaled to thousands of video frames captured during data collection and does not need training. Instead, it retrieves a set of most relevant video frames (e.g. highway vs. secondary road

images that are captured with different polarizations.^{30,31} Agrawal et al. demonstrated a technique to improve vision by capturing two images through the haze with different polarizations.³² further presented a technique to remove flash photography artifacts by processing images taken from different flash exposures. This technique improves image quality by removing unwanted specular reflection from the camera's flash.³³ Raskar et al. developed a technique to capture and convey shape features of real-world scenes. The authors used a camera with a carefully placed set up to detect depth discontinuities and distinguish them from intensity edges due to material discontinuities.

Luminance is perceived by the human viewer as the brightness of a light source.³⁴ The pixel values in an image from a digital camera are proportional to the luminance in the original scene. So, a digital camera can act as a luminance meter. In effect (provided they can be calibrated) each of the millions of pixels in the light sensor becomes a luminance sensor. There are significant advantages using a digital camera for measurement of luminance:³⁵

- A luminance meter is a much more expensive device than an illuminance meter.
- A digital camera captures the luminance of an entire scene. This speeds up the measuring process and allows multiple measurements at the same instant.
- The surroundings of the luminance measurement are recorded, which in turn place measurements in the appropriate context.
- For luminance measurement, the Field of View (FOV) of the sensor must be smaller than the source. The FOV of a luminance meter is about 1°. The FOV of a digital camera pixel is 150 times smaller, so it can measure small area light sources.

The proposed technique in this project is similar to Raskar et al.³⁶ as a carefully designed artificial light source is used to capture the physical aspects of the scene. Different from their approach³⁷ which was designed toward extracting edges and shapes from the image, a retro-reflectivity map is estimated in this research project. In order to do so, an understanding of luminance and illuminance is required. Luminance is perceived by the human viewer as the brightness of a light source.³⁸ By photographing a source of known luminance and calibrating the camera, the conversion factor can be obtained that links luminance (in candela per square meter) to the intensity value of a pixel in an image.

This research aims to address the research question of possibility, specifically with regard to making a decision to replace signs based on High Dynamic Range (HDR) images and daytime retro-reflectivity inspections. HDR photography refers to the method of capturing photographs containing a greater dynamic range than what normal photographs contain.

³⁰ Chen and Wolff, "Polarization Phase-Based Method for Material Classification in Computer Vision."

³¹ Schechner, Narasimhan, and Nayar, "Polarization-Based Vision through Haze."

³² Agrawal et al., "Removing Photography Artifacts Using Gradient Projection and Flash-Exposure Sampling."

³³ Raskar et al., "Non-Photorealistic Camera: Depth Edge Detection and Stylized Rendering Using Multi-Flash Imaging."

³⁴ Hiscocks and Eng, *Measuring Luminance with a Digital Camera*.

³⁵ Wüller and Gabele, "The Usage of Digital Cameras as Luminance Meters."

³⁶ Raskar et al., "Non-Photorealistic Camera: Depth Edge Detection and Stylized Rendering Using Multi-Flash Imaging." ³⁷ Ibid.

³⁸ Hiscocks and Eng, *Measuring Luminance with a Digital Camera*.

They store pixel values outside of the standard Low Dynamic Range (LDR) of 0-255 and contain higher precision. HDR images are widely used by graphics and visual effects artists for a variety of applications, such as contrast enhancement, hyper-realistic art, post-process intensity adjustments, and image-based lighting. As a result, the speed of data collection increases and will be able to enhance daytime data collected for a retro-reflective asset for nighttime condition assessment. In addition to decreasing the agencies cost resulting from manual processes, the proposed system increases the safety of inspection activities through daytime and remote data collection.

III. METHOD

This research proposes a computer vision-based method for measuring the retro-reflectivity of traffic signs. The proposed method, as shown in Figure 4, uses HDR images taken during the daytime, while the surroundings of the luminance measurement are recorded placing the measurements in context. This method involves a process of merging multiple LDR images at varying exposures to create HDR images. By photographing a source of known luminance, one obtains the conversion factor that links luminance in candela per square meter to the value of a pixel in an image. Consequently, the key to calibration is a light source of known luminance. The proposed method requires a consumer-level camera equipped with a flashing device. By capturing two images almost simultaneously, the method simulates nighttime visibility and allows retro-reflectivity to be measured at a level of accuracy and granularity mandated by FHWA.



Figure 4. Method Overview for Image-Based Retro-Reflectivity Measurement during Daytime

A combination of computational photography and carefully tuned hardware are used to generate realistic photos of the night during the daytime. First, two images are captured from a scene; one with a controlled artificial light source, produced by a commercial flash, and one without. Then, the two images are processed to remove all the light sources from the scene except for the controlled light source. Since all natural light sources including the sun are removed, the output image resembles a night photo where only the controlled light source is present. Figure 5(a) and Figure 5(b) illustrate two photographs which have been taken from the same scene during the daytime—one with flash and one without. Figure 5(c) shows the processed night view of the scene generated by removing natural light sources.



Figure 5. (a) Image with Flash; (b) Image without Flash; (c) Night Photo Reconstruction

To synthesize a night photo; one needs to remove the sun and all of its reflections while adding a controlled light source. To do this, two images are captured where a strong light source is present in only one of the two images. The image without the artificial light source is referred as I_{Day} and the image with the artificial light source present is referred as $I_{Flash+Day}$. The two images are processed to estimate a reflection from the controlled light source only and is referred to as I_{Flash} . The general strategy to isolate the controlled light source is to first extract true irradiance and then subtract the two images as: $I_{Flash} = I_{Flash+Day} - I_{Day}$. However, a number of important software and hardware measures must be taken before this step is possible. These measures are outlined in the following section.

CAMERA EXPOSURE CALIBRATION

One way to relight an object is to capture a 360 degree panoramic (omnidirectional) HDR photograph of a scene, which provides lighting information from all angles incident to the camera. Capturing such an image is difficult with standard cameras because it requires both panoramic image stitching and LDR to HDR conversion. An easier alternative is to capture an HDR photograph of a spherical mirror, which provides the same omnidirectional lighting information up to certain physical limitations dependent on sphere size and camera resolution. The author takes the spherical mirror approach, inspired primarily by Debevec³⁹. With this panoramic HDR image, we can plot the response film function for different color channels and calculate pixel values. In order to do so, multiple observations at each pixel with different exposures, as shown in Figure 6, are used, and the image intensities are mapped onto a linear space.

³⁹ Debevec, "Rendering Synthetic Objects into Real Scenes: Bridging Traditional and Image-Based Graphics with Global Illumination and High Dynamic Range Photography."



Figure 6. Creating HDR Images from LDR Images

Nearly all cameras apply a non-linear function to recorded raw pixel values in order to better simulate human vision. In other words, a pixel intensity does not linearly correspond to pixel irradiance (the light incoming to the camera). Therefore, direct subtraction would not preserve intensity ratios due to non-linearity. Rather, this response function depends on camera CCD (Charge Coupled Device) and a number of other factors including exposure time (shutter speed) and f-stop (aperture). The Camera is not a photometer and exhibits a limited dynamic range, with an unknown non-linear response. Hence, in order to convert pixel values to true radiance values, it is needed to estimate this film response function. The solution is to recover the response curve from multiple exposures and then reconstruct the radiance map. For a given camera and with given settings, it is enough to estimate the film response function only once. The response function can then be used consistently without the need for recalibrations.

This response function is estimated according to a technique developed by Debevec⁴⁰ using multiple images. The goal is to create HDR images from LDR images and create an HDR tone-mapping. HDR photography is the method of capturing photographs containing a greater dynamic range than what normal photographs contain (i.e. they store pixel values outside of the standard LDR range of 0-255 and contain higher precision). Typically, the response function is difficult to estimate. Having multiple observations at each pixel at different exposures, image intensities are mapped onto a linear space in order to accurately estimate intensity differences. The formula contains pixel values of Z_{ij} for an image with shutter time Δt_j (ith pixel location, and jth image). Exposure is irradiance integrated over time as expressed as Equations (1). Pixel values are then non-linearly mapped and rewritten to form a linear system.

$$PixelValueP = f(Exposure)$$

$$Exposure = Radiance \times \Delta t$$

$$\log(Exposure) = \log(radiance) + \log(\Delta t)$$

$$\Rightarrow \begin{cases} E_{ij} = R_i \cdot \Delta t_j \\ P_{ij} = f(E_{ij}) = f(R_i \cdot \Delta t_j) \\ \ln f(P_{ij}) = \ln(R_i) + \ln(\Delta t_j) \\ g(P_{ij}) = \ln(R_i) + \ln(\Delta t_j) \end{cases}$$
(1)

⁴⁰ Ibid.

Given that the pixel values Z at varying exposures t, the goal is to solve for $g(p) = \ln(E x t)$ = $\ln(E) + \ln(t)$ where P_{ij} gives pixels near 0 or 255 less weight, R_i is radiance at a particular pixel site which is the same for each image, Δt_j is known shutter time for image j, and $g(P_{ij})$ is exposure as a function of the pixel value.

This boils down to solving for E(irradiance) since all other variables are known. By these definitions, g is the inverse, log response function. The author uses this technique to compute E_{day} and $E_{flash+day}$. This technique is frequently used in HDR photography as it is crucial to have comparable pixel intensity values. In this research, this technique is used to estimate true irradiance.

AUTOMATIC ALIGNMENT

In order to subtract the two images, I_{Day} and $I_{Flash+Day}$, all elements in the images must be perfectly registered (aligned). A bright edge that is misaligned by one tenth of a pixel (or a few arc-seconds) produces a significant artifact around the edges of objects as shown in Figure 7. In real-world conditions, both the camera and objects can move within several pixels. For example, a camera that is fixed on a tripod may be affected by some degree of vibration due to the wind and other factors. Furthermore, some objects such as moving cars and pedestrians may move a few pixels between the times that the two images are being captured. A camera that is mounted on a vehicle or a camera that moves could exhibit a greater degree of such misalignments.



Figure 7. Misalignment Produces a Significant Artifact around the Edges of Objects

To minimize the effects of vibrations and movements, the images are automatically aligned in two steps: (1) global alignment and (2) local sub-pixel alignment.

Global Alignment

In global alignment, images are translated so that the misalignment is below one pixel. Cross-correlation on the edges of I_{Day} and $I_{Flash+Day}$ are computed to estimate global displacement. Here image edges are used rather than raw pixel intensities because the alignment of edges is more accurate than the alignment of raw pixel intensities. To speed up the process of cross-correlation, Fast Fourier Transform is used to complete the process in $0(n \log n)$. The displacement that obtains the maximum alignment is then chosen (See Figure 8). If the camera has not moved, the displacement is zero. This step makes the algorithm robust to displacements.



Figure 8. Cross-Correlation Between the Edges of I_{Day} and $I_{\text{Flash+Day}}$

Local Alignment

In the second step, sub-pixel alignment for local areas is performed. The sub-pixel alignment is essential because at that level, the misalignment is different in various locations of the image. After the process of global alignment, some local misalignments may still exist. Misalignment could be different in different areas of the image due to tiny movements in the scene or the camera. This misalignment produces artifacts at the edges. Local sub-pixel registration is performed in order to align every local patch in the image.

The usual technique is to up-sample images and performs a pixel-wise cross-correlation. The author uses a technique proposed by⁴¹ to align the images without up-sampling. This algorithm registers a pair of images by retrieving the phase difference within a discrete cosine transform. This alignment is performed for a 100×100 grid of patches in the image. Each of the 10,000 blocks is aligned separately according to the local appearance of the block. Figure 9 compares the effect of using local alignment on the quality of the output.

⁴¹ Guizar-Sicairos, Thurman, and Fienup, "Efficient Subpixel Image Registration Algorithms."



Figure 9. (a) Before Sub-Pixel Alignment; (b) After Sub-Pixel Alignment

Irradiance Estimation

After I_{Day} and $I_{Flash+Day}$ are fully registered and the response function g is obtained, E_{Flash} is computed according to the following Equation:

$$E_{Flash} = E_{Flash+Day} - E_{Day} = g(I_{Flash+Day}) - g(I_{Day})$$
⁽²⁾

RETRO-REFLECTIVITY MEASUREMENT

Retro-reflection is the ratio of the amount of light returned from a traffic sign versus the amount hitting the sign. As shown in Figure 10, to determine the retro-reflectivity level of a traffic sign, the measures of luminance, illuminance, and geometry are required.



Figure 10. Component of Retro-Reflectivity

The FHWA has adopted the SI units for retro-reflection; thus by computing the illuminance and luminance, retro-reflectivity is measured in units of candelas per lux per square meter $(cd/lx/m^2)$ as follows:

$$Light INTO Sign = Illuminance = lux (lx)$$
(3)

$$Light OUT of Sign = Luminance = \frac{Candela}{m^2} (cd/m^2)$$
(4)

$$Retro - reflectivity = R_A = \frac{Light \ OUT \ of \ Sign}{Light \ INTO \ Sign}$$
(5)

$$R_A \propto \frac{Luminance}{Illuminance} \left(cd/lx/m^2 \right)$$
 (6)

Equation (7) shows the exact relationship between the luminance of a surface (L) in cd/m², the illuminance (E) in lx and reflectance (p) (dimensionless) where π is the pi number.⁴²

$$L = \frac{E\rho}{\pi} \tag{7}$$

Luminance from Pixel Value

The digital camera turns an image into a two-dimensional array of pixels. Ignoring the complications of color, each pixel has a value that represents the light intensity. The amount of exposure (the brightness in the final image) is proportional to the number of electrons that are released by the photons of light impinging on the sensor. Consequently, the amount of exposure is proportional to the illuminance (in lux) times the exposure time. The brightness, in turn, is measured in lux-seconds. This further invokes the parameters of the camera, whereby the formula is as follows:⁴³

$$N_d = K_c \left(\frac{tS}{f_s^2}\right) L_s \tag{8}$$

Where N_d is the value of the pixel in the image, K_c is calibration constant for the camera, t is exposure time in seconds, f_s is aperture number (f-stop), S is ISO sensitivity of the film, and L_s is the luminance of the scene in *candela/meter*². One measurement would be sufficient to determine the value of calibration constant. User would photograph a source of known luminance L_s , to determine the value N_d of the pixels in the image, and note the camera settings for ISO exposure time and aperture. To calculate the N_d , the red, green, and blue values are simply taken and used the following formula to convert them into a grayscale pixel:

$$N_d = R \times 0.299 + G \times 0.587 + B \times 0.114 \tag{9}$$

The reason these values are weighted is that pure red, green, and blue are darker/lighter than each other, with green being the darkest and blue the lightest.⁴⁴

⁴² Hiscocks and Eng, *Measuring Luminance with a Digital Camera*.

⁴³ Conrad, *Exposure Metering*.

⁴⁴ Johnson, Stephen Johnson on Digital Photography.

Illuminance from Pixel Value

American Standard Association (ASA) has defined incident-light meters as well as reflected-light meters; below is the equation for incident-light exposure:

$$\frac{A^2}{t} = \frac{ES_x}{K_c} \tag{10}$$

Where A is the relative aperture (f-number), t is the exposure time (shutter speed) in seconds, E is the illuminance, S_x is the ASA arithmetic film speed, and K_c is the incident-light meter calibration constant. By placing the luminance and illuminance in Equation (10), the sign retro-reflectivity from every pixel in the images taken during the daytime is measured. Finally, the retro-reflectivity of a sign is measured by averaging all pixel-level measurements. This is consistent with current practices, yet instead of using a few (typically up to four) point-level measurements, all pixels are used to characterize retro-reflectivity more accurately.

IV. EXPERIMENTAL RESULTS AND DISCUSSIONS

For evaluating the performance of image-based retro-reflectivity measurements of traffic signs in during the daytime, several experiments were conducted on different traffic signs with different levels of retro-reflectivity (See Figure 11). The camera used for data collection is Nikon D300 along with Flash Nikon SB-900.



Figure 11. Camera Setup for Data Collection at Different Times of Day and at Different Distances

DATA COLLECTION AND SETUP

HDR images are used for image-based lighting purposes. To derive the omnidirectional lighting information, an HDR photograph of a spherical mirror has been captured (see Figure 12) at six different exposure time, while the response curves are plotted using the formulation in Equation (1). Figure 13 shows these response curves for different color channels. As mentioned, this calibration is a one-time process for each camera and does not need to be repeated for field experiments.



Figure 12. An HDR Photograph of a Spherical Mirror at Six Different Exposure Time



Figure 13. Response Curve for Different Color Channels

The experiments were conducted in both sunny and cloudy weather conditions four times of day: 9:00 AM; 12:00 PM; 3:00 PM; and 6:00 PM and at six distances of 25 *ft*, 50 *ft*, 75 *ft*, 100 *ft*, 200 *ft*, and 250 *ft*. In these experiments, the camera was facing East, which represents the most extreme measurement condition. Camera setting for data collection is shown in Table 2.

| Table 2. | Camera Setting for Data Collection |
|----------|------------------------------------|
|----------|------------------------------------|

| Flash Power | ISO | Exposure Time | Shutter Speed | Focal Length |
|-------------|-----|---------------|---------------|--------------|
| 1/1 | L1 | f/16 | 400 | 70 |

PERFORMANCE EVALUATION

In order to compare the performance of the proposed technique, the as-is retro-reflectivity of traffic signs were benchmarked. The results of this measurement are shown in Table 3 where blank represents measurement when there are no traffic signs.

Table 3. Results of Ground Truth

| Traffic | Speed Limit | Warning | Retro-Reflective | Non-Retro-Reflective | Blank |
|--|-------------|----------|------------------|----------------------|--------|
| Sign | Sign | Sign | Stop Sign | Stop Sign | |
| Retro-reflectivity (cd/lx*m ²) | 147.625547 | 13.21307 | 17.486476 | 0.115547 | 0.0503 |

RESULTS

To check the reliability of the proposed method, several experiments have been carried out. Four different traffic signs with different levels of retro-reflectivity were used to test the performance of the image-based method for retro-reflectivity measurement in the daytime. Figure 14 shows the results of image-based retro-reflectivity measurement for the speed limit, warning, and retro-reflective stop signs respectively. The retro-reflectivity of each sign at different times of day and for different distances are measured in cd/lx^*m^2 and are compared with the ground truth. In most cases, the measurement shown is above the ground truth values shown in Table 3. In a few cases, the measured retro-reflectivity numbers are below the ground truth. These are mainly due to distance and the time of day when data was collected.



Figure 14. Reconstructing Nighttime Images from Images Taken in the Daytime

To obtain the criteria for the best performance, the impact of distance and lighting condition (the timing of the experiment) on the accuracy of measurement were examined and have been outlined in the section below.

Impact of Time

Figure 15 compares the retro-reflectivity measurements for different traffic signs at different times of the day. Compared to ground truth, the proposed method with the camera facing East (i.e. the worst measurement condition) works properly at 9:00 AM, 12:00 PM, and 3:00 PM and for all distances less than 75 *ft*. However, the performance of the method is decreased as the measurement time approaches the timing of the sunset. The decrease is due to the alignment of the sunlight direction and the camera flash light source direction (West-East). As shown in most extreme cases (6:00 PM), when these directions are aligned, the methods with the current hardware setting do not result in accurate measurements.



Figure 15. Impact of Time on Image-Based Retro-Reflectivity Measurement for Different Types of Traffic Signs at Different Distances

Impact of Distance

Figure 16 compares the measurement of retro-reflectivity for different traffic signs at different distances. As shown, the proposed method works pretty well for distances less than 75 ft in all the times during the day. However, the method is not robust enough for distances above 100 ft and more especially in more extreme light conditions (3:00 PM

and 6:00 PM). Nevertheless, the method with the current hardware setting is capable of measuring the retro-reflectivity of traffic signs for distances less than 75 *ft* at all times in the day. The accuracy and granularity of the measurements show that the technique complies with FHWA requirements.



Figure 16. Impact of Distance on Image-Based Retro-Reflectivity Measurement for Different Types of Traffic Signs at Different Times

DISCUSSION

By contrasting measurements obtained from the proposed method with lab measurements (ground truth), the method shows an accuracy of 88.8%+ in terms of correctly clarifying the measured retro-reflectivity levels as accepted or not. Table 4 summarizes these statistics for different types of signs. For speed limit sign with ground truth retro-reflectivity of 147.625547 (*cd/lx*m²*), the method does not produce accurate results at the distance of 250 *ft* and at any time between 3:00 to 6:00 PM. The proposed method also does not result in accurate measurements on the warning sign, at 6:00 PM for distances more than 75 *ft*, and at time 3:00 PM for distances more than 100 *ft*. The same situation applies to retro-reflective stop sign. Based on current hardware and software settings, the proposed method can measure retro-reflectivity with signs at 97.70% accuracy for all distances between 25 *ft* and 100 *ft* and at any time between 9:00 AM to 3:00 PM.

| Retro-Reflectivity Measurement | Speed Limit Sign | Warning Sign | Stop Sign |
|--------------------------------------|------------------|--------------|-----------|
| Ground Truth (cd/lx m ²) | 147.63 | 13.21 | 17.49 |
| Mean of Image-Based Measurements | 156.58 | 13.26 | 18.64 |
| Standard Deviation | 9.37 | 0.49 | 1.74 |
| Error | 6.41% | 1.25% | 6.62% |
| Accuracy | 93.59% | 98.75% | 93.38% |
| Average Accuracy | 95.24% | | |

Table 4. Performance of Proposed Method

Compared to the current practice of using the retro-reflectometer where only a few measurements are conducted (typically four point-level measurements on sign background, and four point-level measurements on sign text), the method considers the entirety of the traffic sign surface and results in a more comprehensive retro-reflectivity measurement. This is important as traffic signs exhibit heterogeneous deterioration rates, whereby point-level measurements may not be the best representatives for the entirety of the sign surface. Considering current practical limitations, even when the most accurate retro-reflectometers are used, the method at 97.70% accuracy shows significant promise for large scale applications.

V. CONCLUSION

One of the key measures for roadway safety at nighttime is sign visibility. Evaluation and replacing traffic signs with low retro-reflectivity is an effective strategy for improving the safety of transportation systems. With new FHWA requirements on sign retro-reflectivity as outlined in MUTCD, road agencies require cost-effective techniques that can enable retro-reflectivity measurement during the daytime. To this end, the research presented in this paper and validated a new image-based method for measuring the retro-reflectivity of traffic signs during the daytime. The method has the potential to provide quick, safe, and inexpensive compliance inspection for a minimum level of retro-reflectivity in traffic signs. With the hardware mounted on a driving vehicle, these measurements can be taken remotely and automatically for longer stretches of roadways and highways, and there is no further need for putting measurement equipment in contact with a sign and repeating the manual process for one sign at a time.

Measurements can also be taken from real roadway geometries rather than prescribed geometries which do not always represent the real world conditions. In particular, the retro-reflectivity of twisted and leaning signs can also be measured under real roadway conditions and for actual driver-view perspectives. The method was evaluated with ground truth and showed that the proposed image-based method with current hardware setting is robust enough to measure retro-reflectivity of signs at different times of the day and for any distance less than 100 *ft*. Such a mobile setup can significantly facilitate the current process by allowing inspection vehicles which are widely used in the U.S. to measure retro-reflectivity levels during the daytime. This method can also minimize the challenges associated with inspecting overhead and difficult-to-reach ground-mounted signs.

ABBREVIATIONS AND ACRONYMS

| AMAC | Advanced Mobile Asset Collection |
|----------|--|
| ASA | American Standard Association |
| ASCE | American Society of Civil Engineers |
| CalTrans | California Departments of Transportation |
| CCD | Charge Coupled Device |
| FHWA | U.S. Federal Highway Administration |
| FOV | Field Of View |
| HDR | High Dynamic Range |
| LDR | Low Dynamic Range |
| MUTCD | Manual on Uniform Traffic Control Devices |
| SMARTS | Sign Management and Retro-reflectivity Tracking System |
| VISULISE | Visual Inspection of Signs and Panels |

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PI Vahid Balali, PhD, is an Assistant Professor in the Department of Civil Engineering and Construction Engineering Management at California State University Long Beach. He is a member of National Center for Transportation, Green Technology, and Education (TransGET). Dr. Balali's research focuses on the visual data sensing and analytics, virtual design and construction for civil infrastructure and interoperable system integration, and smart cities in transportation for sustainable decision-making. His research interests include experimental and computational approaches for image-based recognition, 3D localization, and retro-reflectivity evaluation of civil infrastructures for enhanced condition assessment. Through his research and work experience, he has been involved in several software and hardware developments that resulted in many research prototypes. He also has experience as a visual data analyst and developed a video-based construction resource tracking and action recognition for activity analysis of operators at Caterpillar. He has the knowledge, technical skills, and experience that are crucial to the successful completion of the proposed work.

He was selected as one of the Top 40 under 40 by the Consulting-Specifying-Engineer for the year 2017 and top young professional in California by the Engineering News Record (ENR) for the year 2016. He has received the 2014 second best poster award from the Construction Research Congress, and 2013 CMAA national capital chapter scholarship award. He is currently an associate member of ASCE and CMAA, committee member of the ASCE Data Sensing and Analysis and ASCE Visual Information Modeling and Simulation committees, and friend member of relevant TRB committees. He is also serving as a reviewer of several top-notch Journals. He is actively collaborating with industrial partners and is involved in professional and outreach activities.

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