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The National Surface Transportation Safety
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Development and Validation of a Luminance Camera

Final Report

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Lighting | Technology
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EXECUTIVE SUMMARY

Under the sponsorship of the National Surface Transportation Safety Center for Excellence (NSTSCE), an effort was undertaken to develop a system of image capture to analyze luminance data gathered in naturalistic driving research. Currently there exist still photometers to capture luminance data in an image, as well as hand-held luminance meters to capture luminance data in the environment. However, still photometers are unable to capture rapidly changing luminance data, and hand-held luminance meters are both time consuming to operate for multiple areas of interest within a scene, as well as lacking in the ability to capture an image of the scene. Therefore, the current effort was focused on the development of a system for video capture of the dynamic, ever-changing luminance environment. This system would allow for both analysis of the dynamic scene as well as possession of video frames for future analyses.

Methods

The primary method used in this research was the calibration of smaller, more mobile luminance cameras through the use of an imaging photometer. In a controlled, static environment, images were captured simultaneously with both the luminance cameras as well as the imaging photometer. The luminance cameras enable adjustments to gain, shutter, and exposure variables; and data were collected through varying combinations of such hardware configurations.

Using known variables, such as gain and shutter and luminance camera returned grayvalues, the luminance was determined and compared to photometer-measured luminance. The accuracy of such comparisons was determined.

Following this static calibration, luminance cameras were then installed in a vehicle and data were collected through a range of dynamic environments. Cameras were manually set to known gain and shutter values to capture a range of luminance values.

Results

Through calibration, relationships of luminance camera gain and shutter to luminance were determined. With manual control of luminance camera variables, the luminance values of a captured image can now be estimated with a high degree of accuracy, based on the grayvalues normally resulting from the luminance camera. Prediction results were compared to actual luminance recorded values, and an additional evaluation of data collection repeatability and reproducibility (R&R) was conducted. R&R evaluation results indicate the luminance camera is highly repeatable and capable of reproducing consistent data through multiple trials.

Discussion

The calibration of a luminance camera for recording luminance data was found to be successful with a relatively high level of accuracy, based on comparisons to known luminance values. Due to the level of saturation of an image being so highly dependent on camera gain and shutter values, there are recommendations for the configuration of camera gain and shutter values. Possible areas of future research would include efforts to decrease the temperature of the luminance camera in order to increase the signal and decrease noise, considerations of spectral distribution, as well as improvements in the calibration procedure.

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LIST OF ABBREVIATIONS

ADC	analog-to-digital converter
AIAG	Automotive Industry Action Group
CCD	charge-coupled device
HPS	high-pressure sodium
NSTSCE	National Surface Transportation Safety Center for Excellence
R & R	repeatability and reproducibility
VTTI	Virginia Tech Transportation Institute

CHAPTER 1: INTRODUCTION

In a dynamic setting, there are many factors to consider when investigating the luminance of objects in a scene. The visibility of objects such as pedestrians or pavement markings will be greatly affected in a constantly moving environment. It is also almost certain that these factors will vary as the scene continues to change with each moment. In a moving vehicle, for example, the luminance of objects will constantly change. For example, the figure below demonstrates this principle.

Figure 1. Photo. Luminance changes in pedestrian from overhead lighting (left) to no overhead lighting (right).

The figure displays a pedestrian photographed from a moving vehicle. The pedestrian is walking on the sidewalk in the same direction as the moving vehicle. The moment captured in the left part of the figure was occurring when the pedestrian was directly underneath an overhead street luminaire. The image on the right occurred seconds later as the pedestrian had passed the luminaire and the vehicle was about to pass the pedestrian. In a matter of seconds there are changes in the luminance of the pedestrian's shirt and legs, which occur due to both the pedestrian's and the vehicle's changing locations in the environment. Characteristics that would make this pedestrian visible at night, such as the luminance of clothing, are constantly changing. It is for this reason the dynamic aspect of the environment needs to be taken into consideration.

Therefore, there is a need for a more dynamic method to measure such changes. Currently, luminance meters may be used to obtain luminance values at designated locations in the environment. However, this becomes time consuming when the scene is large, as well as impractical due to the dynamic nature of the scene. Once measurements are taken with a hand-held luminance meter, that scenario cannot be identically re-created to gather data. The use of photometers to capture images for future analysis then becomes an advantage over luminance meters, as it allows the user to record a still image of the scene for later data analysis.

A charge-coupled device (CCD) photometer enables the user to capture still images with resulting luminance values. These values (measured in candelas/meter^2) are the amount of luminous energy given off by the surface of the object. There is even an effort to use still digital cameras as luminance meters (Wuller & Gabele, 2007)(1). It is at this point that calibration of a digital image capture device is a necessity. Through adjustments in shutter, exposure, and other variables, it has been shown that such a calibration is possible (Kao, Hong, & Lin, 2005)(2). However, using this still-image capture method would still be insufficient for an experimental dynamic setting in a vehicle. The aim of this current research is to design a system of dynamic data collection through a digital video camera. The results of the video capture would then be related to known luminance values, in an effort to calibrate the video camera as a "luminance camera" capable of determining the luminance of objects in a scene.

Following a calibration of the luminance camera in a controlled, immobile environment, an evaluation of the capabilities of the camera in a dynamic test area would be necessary. This would serve the purpose of confirming a proper configuration of camera settings. These settings would be those that ensure clarity of the image, while also maintaining accuracy in a calibration model.

The repeatability and reproducibility of the new luminance camera system would also need to be determined. An example of how to determine this is to employ a Gage R&R tool. Gage R&R is an evaluation method to determine the level of certainty one may have that resulting data is consistent over time (repeatability) and among different users (reproducibility). A Gage R&R evaluation was conducted in a dynamic environment with multiple users.

Research Objectives

The objectives for this study are to:

- Calibrate a digital camera to a known photometric level
- Develop a rapid method of image capture for calibration calculations
- Develop a working system for video capture in a dynamic setting
- Evaluate multiple camera settings to determine an optimal manual (user-determined) configuration or possibility of an auto (camera-determined) configuration
- Determine a level of confidence that resulting data is consistent and reliable

CHAPTER 2: SYSTEM OVERVIEW

DESIGN

The cameras chosen for the design of the dynamic system were Point Grey Grasshopper digital cameras. The Grasshopper is an IEEE-1394b device allowing high data transfer rates (800Mb/s) as well as allowing “daisy chaining”, or direct connection, with other similar cameras. The Grasshopper allowed the adjustment of imaging variables such as shutter time (ms), gain (dB), and exposure (EV). This camera was capable of recording 16-bit video with pixel “grayvalues” ranging from 0 to 65,520. The grayvalue is a unitless number assigned to each pixel.

The MATLAB Image Acquisition and Processing Toolboxes were implemented as compatible software for calibration of the Grasshopper. This allowed for highly automated image capture and pixel extraction during the calibration process. The FlyCap image capturing software accompanying the Grasshopper was also employed for the more dynamic, in-vehicle portions of the study.

In order to capture multiple hours of data, setup of the data acquisition system included the addition of an external hard drive and Firewire hub (figure 2).

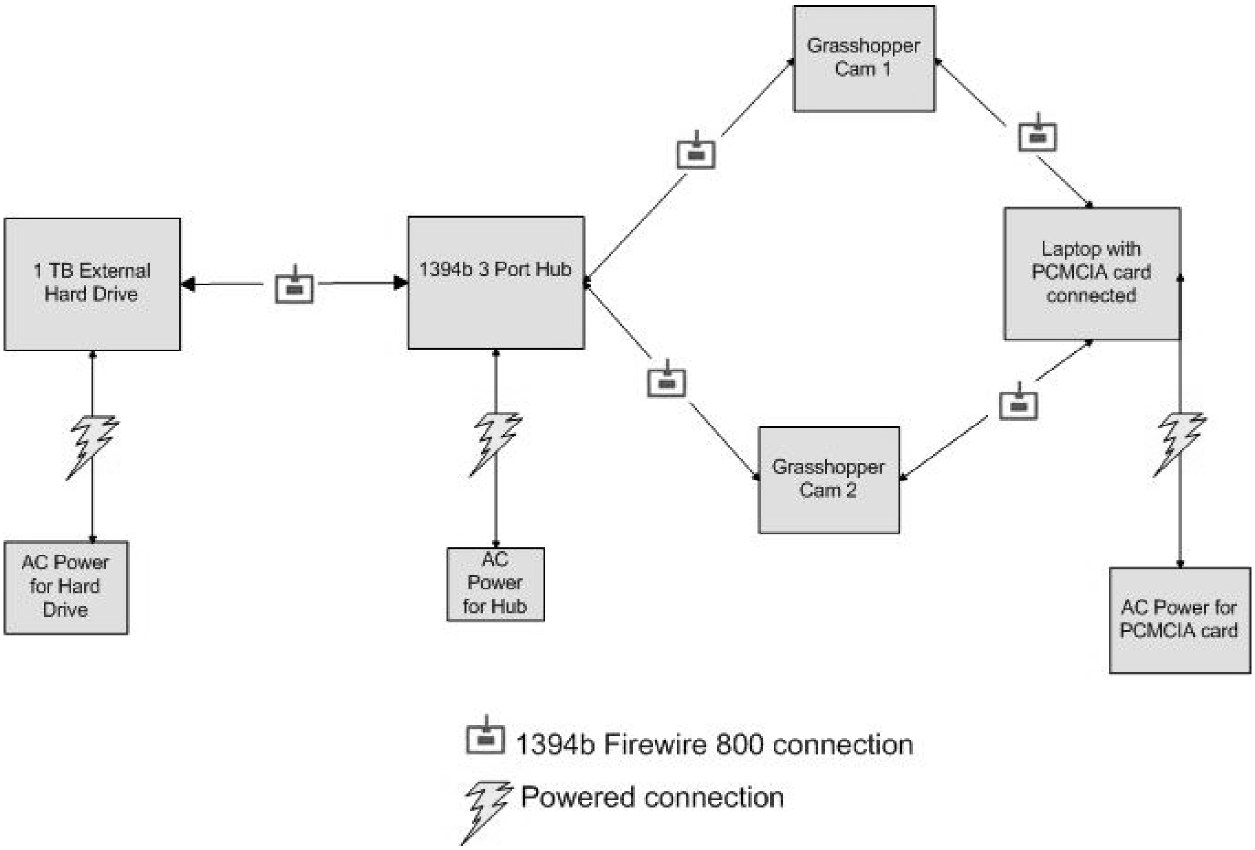


Figure 2. Diagram. System setup for dynamic acquisition.

CHAPTER 3: CALIBRATION

METHODOLOGY

Levels of light intensity were manipulated during calibration in order to capture a range of luminance from a set of targets marked on a vertical white surface (figure 3).

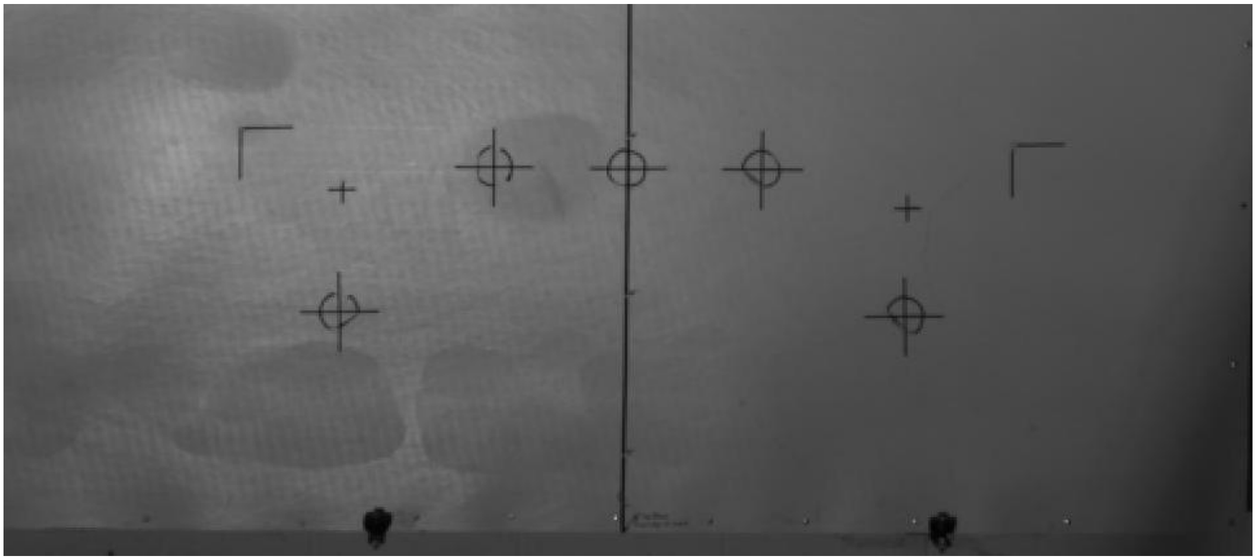


Figure 3. Photo. Calibration board.

Camera settings such as gain and shutter, were also adjusted throughout calibration in order to determine the effect such settings have on camera output. Dependent measures were the luminance camera's grayvalues and the photometer's luminance.

Table 1. Independent Variables - Controlled, Still Environment.

Variable	Levels
Light Level (cd/m^2)	24.1, 15.6, 7.99, 1.87
Camera Gain Level (dB)	24, 21, 18, 15, 12, 9, 6, 3, 0, -2.25
Camera Shutter Level (ms)	267, 213, 159, 105, 51, 41, 36, 31, 26, 21, 16, 11, 6, 1

Following the calibration in a still environment, cameras were installed in a vehicle for dynamic evaluations. Variables under manipulation were gain and shutter. The gain setting may be considered the conversion factor between the number of photons captured by the sensor of the camera and the raw value in a digital value. This digital value is a result of the analog-to-digital converter (ADC). Ideally, this conversion factor would be a minimal value (indicating that the number of photons and the actual raw value converted are directly proportional to each other). The shutter value is the length of time the camera shutter is opened in milliseconds.

Equipment

This study employed a Radiant Imaging ProMetric series imaging photometer as the basis for calibration. This device returns 1024 x 1024 images containing pixels with luminance values. A hand-held Minolta CS-100 Luminance Meter was equipped in order to estimate luminance values during calibration. The source of light for the calibration process was an incandescent 200-watt light bulb.

Procedure

In a controlled environment, images were captured simultaneously through both the Radiant Imaging photometer and multiple Point Grey Grasshoppers. Lighting conditions were manually adjusted with a single incandescent bulb, to capture images at 4 lighting levels through an estimated range of 1 to 25 cd/m^2. The range was confirmed using a hand-held luminance meter at 4 light levels. These levels as adjusted were approximately 24.1cd/m^2, 15.6cd/m^2, 7.99cd/m^2, and 1.87cd/m^2. Images were captured from the brightest condition first, then manually decreasing ambient light.

Camera settings on the Grasshoppers were adjusted at controlled intervals of shutter, gain, and exposure in order to determine the relationship of these variables to the image output of the camera. These variables were automatically adjusted through the use of the MATLAB programming software.

For the Grasshopper model of camera, the exposure variable (when auto-enabled) adjusts gain and shutter in order to achieve a user-specified average intensity of the image. However, for the purposes of this study, exposure was manually enabled and therefore had no effect on the resulting images.

Following data collection, a specific area of the calibration board was isolated and an overlay of images was conducted. Images captured with the ProMetric photometer were resized and overlaid with the Luminance Camera image. Photometer images were resized in order to accommodate for the different resolutions between the photometer and Luminance Camera. Calculations were then conducted for all pixels in the isolated calibration board area.

Data Analysis

Camera gain and shutter properties were investigated for trends and their relationship to grayvalues in images. A level of pixel saturation was selected based on results in the controlled calibration procedure. One of the first steps was to gain an understanding of the relationship between these adjustable settings of gain and shutter, and resulting grayvalues. Based on this and the point at which images would become saturated, a luminance calibration model was then formulated. In order to determine whether a single calibration formula or multiple formulas would be appropriate as model for calibration, the slopes of the gain and shutter data were calculated. The slopes of interest were those associated with each gain and shutter combination. The result of these efforts was a model that may be used to convert known grayvalues to luminance.

The accuracy of the model was then determined through an analysis of predictions of luminance. Specifically, this involved determining what percentage of predicted or calculated luminance was within 15% of the actual luminance (recorded by the ProMetric photometer).

RESULTS

The beginning of the calibration process involved an understanding of the relationships of camera gain and camera shutter to the grayvalues output from the Luminance Camera. The results for a single light position are shown below.

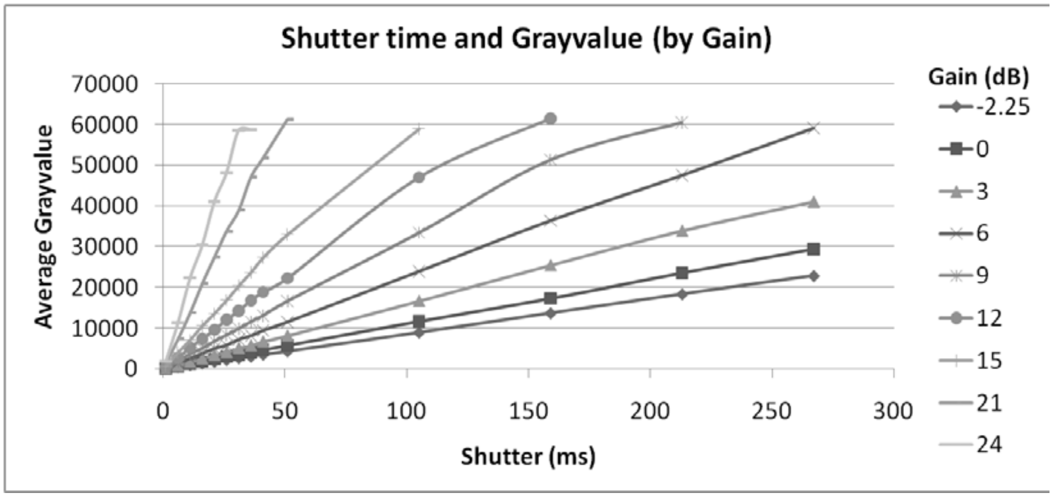


Figure 4. Diagram. Relationship of shutter to grayvalue.

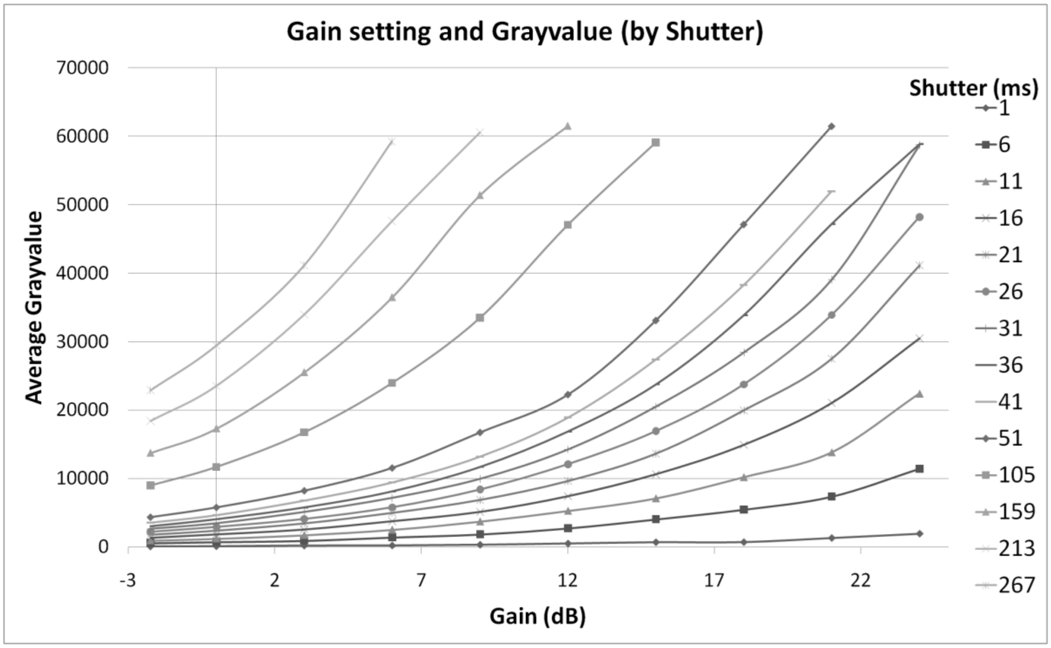


Figure 5. Diagram. Relationship of gain to grayvalue.

While both trends are positive in nature, the relationship of gain to grayvalue (figure 5) was shown to be more logarithmic, than directly linear. Also interesting to note is the data associated with a shutter time of 1ms (also figure 5). While the gain setting increases to its maximum, there is only a slight increase in resulting average grayvalue. Due to this behavior, it was difficult to draw conclusions based on data from a 1ms shutter time.

The point at which the camera's grayvalue level became saturated was another factor to take into consideration. The camera's grayvalue was largely dependent upon the shutter and the gain settings at which the image was captured. An understanding of this level of saturation was important in the further selection of reliable data during analysis. This is presented below in figure 6.

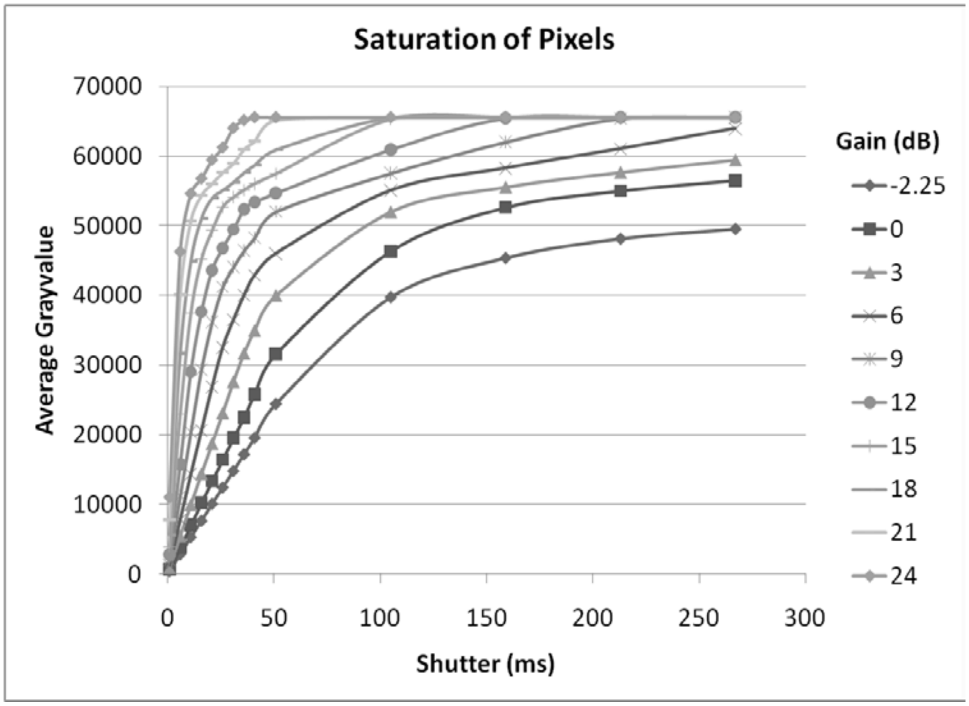


Figure 6. Diagram. Saturation of image pixels.

Based on the camera's 16-bit capabilities, the maximum grayvalue was 65,520. In order to maintain accurate calculations, valid grayvalues below 55,000 were chosen so as to avoid incorporating saturated values. Also, based on the results in figure 6**,** any data from a shutter value above 213ms were considered too saturated to draw inferences from it.

With an understanding of the relationships of camera variables and concentrating on the most appropriate and accurate data, the specific slopes associated with each gain and shutter combination were determined. This was necessary in order to begin building the model or models for calibration of the camera. The slopes are displayed in figure 7.

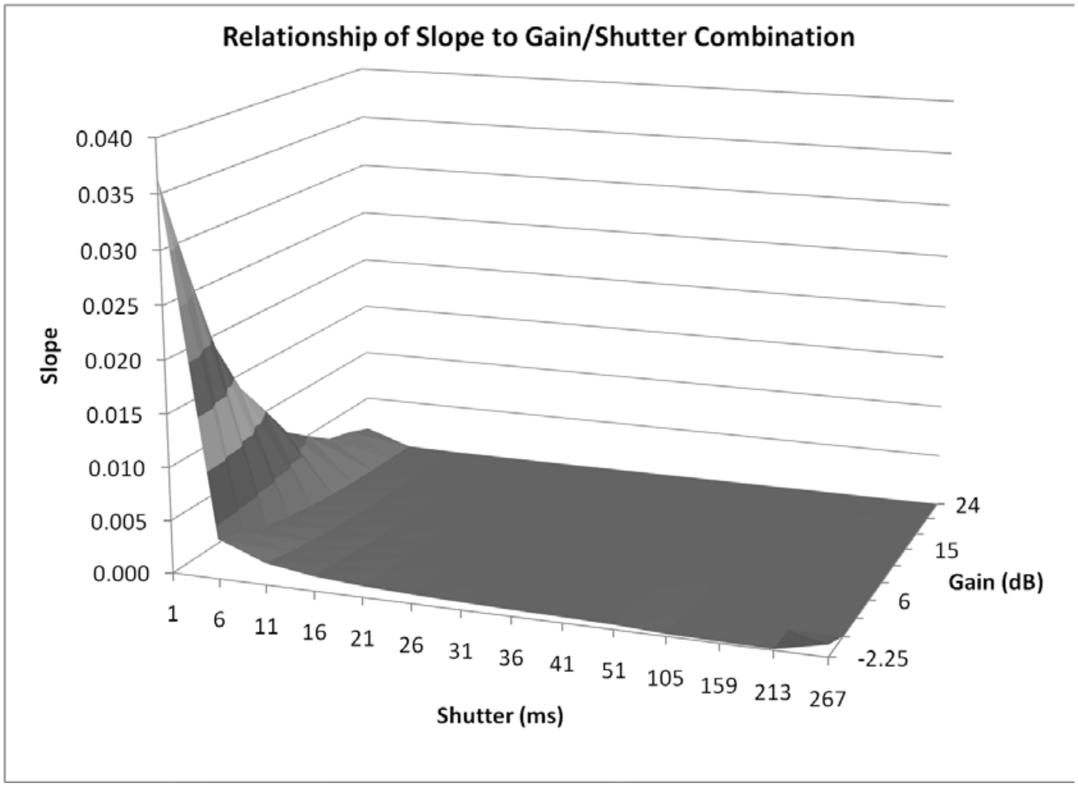


Figure 7. Diagram. Slope relationship to gain and shutter.

The specific slope values then became most effective in the direct development of calibration equations. For example, with a known gain and a known shutter, the respective slope of their combination was used as a multiplier to grayvalue to result in luminance. This is depicted as Equation 1.

Equation 1

$$Slope\ Prediction\ of\ Luminance = Grayvalue * Slope\ of\ Gain\ \&\ Shutter\ Combination$$

A single equation to apply to all data was also developed. This was done in order to determine whether the multiple equations of the Slope Prediction of Luminance would be more accurate as a predictor than a single model. This equation (Equation 2) was the result of a nonlinear regression analysis of all data to arrive at single prediction formula.

Equation 2

$$Nonlinear\ Prediction\ of\ Luminance = Grayvalue * 0.0143 * Shutter^{-0.9827} * e^{-0.1174*Gain}$$

Results of a comparison between the strength of the Slope Prediction of Luminance and the Nonlinear Prediction of Luminance are presented below (table 2) separated by luminance ranges (or bins) of collected data.

Table 2. Percent of predicted luminance within 15% of actual luminance.

	Slope Prediction of Luminance	Nonlinear Prediction of Luminance
bin 1 (1cd/m^2 - 4cd/m^2)	87.24%	86.95%
bin 2 (4.1cd/m^2 - 9cd/m^2)	91.78%	91.58%
bin 3 (9.1cd/m^2 - 15cd/m^2)	99.75%	99.75%
bin 4 (15.1cd/m^2 - 23cd/m^2)	100.00%	99.71%

Based on these results, the Slope Prediction of Luminance as a whole was found to be a slightly more accurate method of predicting luminance based on given grayvalues, gain, and shutter settings. While there is no statistically significant difference between the two methods, the slightly higher percentage of correct predictions increases the likelihood of accuracy of data. It is also interesting to note that the accuracy of predictions increased with increasing luminance. The reason for this was most likely due to the large margin of error as luminance increased. For example, for an actual ProMetric measured luminance of 20cd/m^2, the prediction was allowed to be within 3cd/m^2. However, for a ProMetric measured luminance of 2cd/m^2, the margin of error is reduced to within 0.3cd/m^2. It should be noted that the average difference between predicted luminance and actual luminance across all ranges was 0.31cd/m^2.

An interesting aspect of the gain variable that became apparent at this stage of the calibration process was the behavior of data associated with a gain of -2.25dB. While it would be most beneficial to keep this gain attribute at a minimum (in order to minimize noise), the predictions based on data collected at a setting of -2.25dB were found to deviate from the actual luminance measured by the ProMetric photometer by as much as 6cd/m^2. With this type of unreliability, it was determined that this gain setting would not be considered in further data analysis or in the final manual configuration of the luminance camera system.

An aspect to consider when determining the strength of the calibration factor (the Slope of Gain & Shutter Combination derived for use in Equation 1) is the level of variation between pixels in the calibration image. Specifically, for a selected gain and shutter combination of 0dB and 26ms, the level of variation among pixel slope calibration values for the two extreme lighting setups (Light Setup 1's mean luminance of 2.115cd/m^2 and Light Setup 4's mean luminance of 27.894cd/m^2) is shown in figure 8.

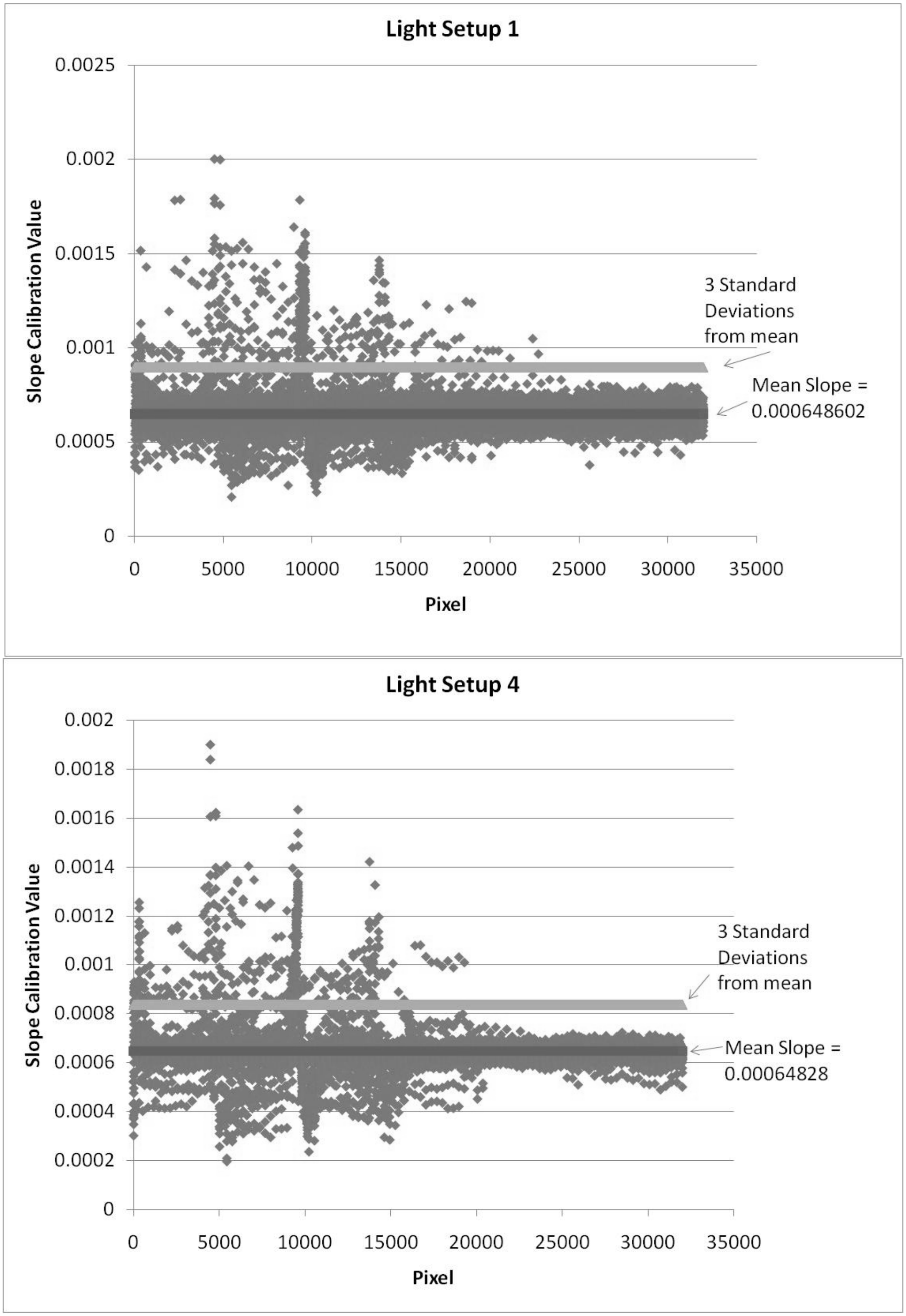


Figure 8. Graph. Pixel to Pixel Variation Based on Select Gain and Shutter Combination.

As one can see from the above figure, the calibration factor for the given gain and shutter combination remains relatively similar regardless of luminance. The mean slope calibration value for this particular gain and shutter combination for Light Setup 1 is 0.000648602 and for

Light Setup 4 it is 0.00064828. However, despite similar mean values, there still exist pixels with associated calibration values that are beyond three standard deviations from those means. One possible explanation for this is the quality of the board used for the calibration purposes. The purpose of the calibration board is to act as a controlled surface for the reflectance of the light to the photometer and Luminance Camera. However, the surface is currently inadequately painted to allow for a proper reflectance.

DISCUSSION

The calibration of the luminance camera system involved the development of both multiple equations based on specific gain/shutter slopes, as well as a single equation. While the benefit of the multiple equations is a slightly more accurate prediction of luminance, the drawback is the lack of flexibility with the configuration of the camera. For example, the slopes generated for a gain setting of 0dB and 3dB, or a shutter of 16ms and 21ms do not apply to images captured with a gain of 2.5dB and shutter duration of 18ms. If the user of the system were interested in capturing images at such a configuration, the application of generated slopes is not appropriate. However, the use of the single equation does not rely on a known slope, and can therefore be applied to gain and shutter configurations not addressed in the current study. As has been demonstrated though, there is a sacrifice in the level of accuracy of using a single equation to predict luminance across all possible gain and shutter combinations.

CHAPTER 4. DYNAMIC EVALUATION

METHODOLOGY

Experimental Design

The specific Luminance Camera settings offered multiple ranges of luminance coverage. The coverage of luminance was determined through analysis of static calibration data. The specific settings chosen for dynamic evaluation are shown in table 3.

Table 3. Independent variables - dynamic environment.

Variable	Levels
Camera Gain Level (dB)	Auto, 24, 21,15, 9, 6, 3, 0, -2.25
Camera Shutter Level (ms)	Auto, 51, 41, 31, 26, 21, 16, 11, 6, 1

Cameras were enabled for auto-adjustment of gain and shutter values in order to compare the quality of such images to those captured through manual manipulation of values.

Equipment

Following the static calibration of luminance cameras, there was a dynamic evaluation of the realistic visibility of select gain and shutter combinations. This was conducted in a Cadillac Escalade with standard headlamps driven by researchers on this study. Two cameras were mounted beneath the vehicle's rearview mirror (figure 9).

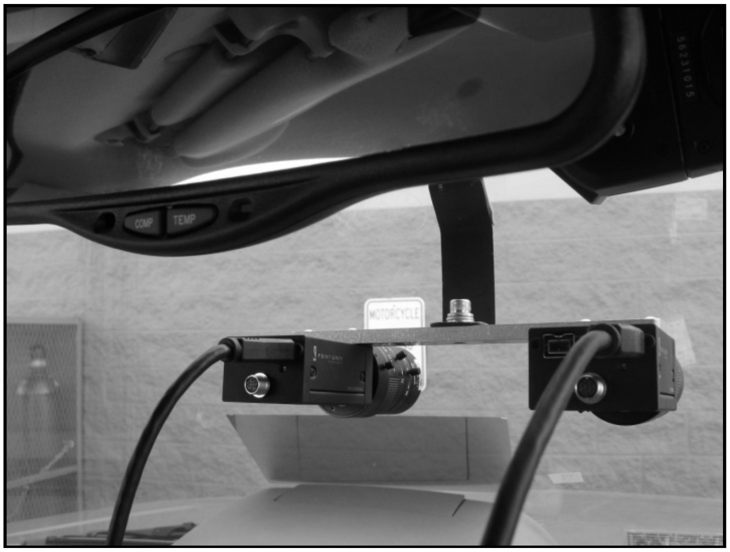


Figure 9. Photo. Luminance cameras mounted.

Procedure

For the dynamic portion of determining suitable camera settings, two cameras were instrumented in a researcher-operated vehicle. Each camera was pre-configured to a specific gain and shutter combination setting for image capture. Approximately 20 minutes of footage were captured through vehicle-populated environments consisting of both presence and absence of overhead lighting. Locations include highways, rural roads, “downtown” locations, and intersections. This was completed six times with a total of 12 combinations of gain and shutter settings, including an instance with an auto-enabled camera continually adjusting gain and shutter.

Images were captured at a rate of 3.75 frames per second. This translates to the capture of an image approximately every 13.7 feet at a traveling rate of 35 mph. The resolution for each image was 1024 x 768, which was the maximum size for the system’s reliable stream of images from two cameras simultaneously onto an external hard drive.

RESULTS

With an understanding of the behavior of gain and shutter, the next steps of the process include a decision of the ultimate manual configuration of the camera system, for the dynamic evaluation as well as future research. Based on the grayvalue level of 55,000 (due to the previously discussed level of pixel saturation), and a subset of pixel data, the maximum luminance being addressed by each gain and shutter combination was determined (table 4). These luminance values were calculated from the gain and shutter and are meant to be used as an estimate of the maximum luminance that can be accurately addressed by each combination.

Table 4. Maximum luminance (cd/m^2) calculated by gain and shutter.

	Shutter (ms)													
Gain (dB)	**1**	**6**	**11**	**16**	**21**	**26**	**31**	**36**	**41**	**51**	**105**	**159**	**213**	**267**
-2.25	899.4	172.6	96.2	66.6	48.4	40.6	34.7	30.1	26.5	21.7	10.8	14.0	6.8	7.3
0	732.1	120.8	69.1	47.2	39.3	32.2	25.9	23.2	20.7	15.8	7.8	5.4	3.6	3.0
3	477.8	89.3	49.2	34.9	26.8	21.7	19.3	15.0	14.0	12.5	5.5	3.5	2.7	2.2
6	332.8	64.0	35.1	24.5	19.4	15.2	13.3	12.6	9.9	7.7	3.7	2.5	1.9	1.6
9	214.1	40.6	23.4	17.6	12.6	10.0	9.6	7.7	6.1	5.5	2.8	1.7		
12	165.4	33.6	18.6	12.0	9.7	7.5	6.1	5.6	5.2	3.9	2.0			
15	107.3	22.9	12.7	9.8	6.8	5.4	4.4	3.7	3.2	2.7	1.7			
18	81.2	14.8	8.2	6.2	3.9	3.2	2.5	2.4	2.0	1.8				
21	56.1	12.1	6.9	3.8	3.3	2.6	2.2	1.8	1.8					
24	41.8	7.0	5.2	2.4	2.0	1.8	1.8	1.7						

Using table 4 as a reference, gain and shutter combinations were selected for the dynamic evaluation of the camera calibration. The route of highway, rural, and downtown locations was driven with cameras pre-set to select gain and shutter combinations. A gain value of 21dB and a shutter value of 21ms (maximum luminance of 3.261cd/m^2) were chosen for viewing areas on the lower level of the luminance range of interest. Examples of these areas include pavement markings and pavement. A gain value of 6db and shutter of 11ms (maximum luminance of 35.121cd/m^2) combination was determined as a higher luminance level setting in order to capture accurate measurements of areas such as road signage text and brighter pavement markings that exceed the maximum of the lower luminance level setting.

The dynamic evaluation of the camera system was successful in the areas of hardware operations and system design. One area addressed was the decision to manually configure the luminance camera system for future research, rather than allow the system to determine hardware settings. The figure below addresses this issue.

Figure 10. Photo. Comparison between manual (left) and auto (right) enabled settings.

Referring to figure 10, one can see the level of blur and saturation that occurs in the camera when enabled to automatically adjust gain and shutter. Inaccurate data measurements in the auto-enabled image are therefore inevitable, so it is for this reason that a manual configuration was chosen as the means of collecting data.

A further understanding of the luminance camera data was attained specifically through a comparison of the two luminance ranges used. These ranges were reached by manually setting cameras to specific gain and shutter values based on table 4. The figure below is an example of such a comparison.

Figure 11. Photo. Comparison between higher gain/shutter (left) and lower gain/shutter (right).

The higher gain and shutter settings (figure 11, left), while appearing brighter, result in reaching the level of saturation much quicker than a lower gain and shutter combination (right). The results of the higher gain setting also contain more noise in an image, therefore making data analysis less reliable. These results, as well as the data indicating the wide range of luminance that may be addressed by lower gain and shutter settings (table 4), led to the conclusion that gain and shutter will be manually configured to be kept at minimal values. However, also taking into consideration the inability to draw effective conclusions from the absolute minimum settings of gain (-2.25dB) and shutter (1ms), the extreme values are not necessarily the ideal choices for configuration.

Therefore, a further understanding of the strength of each gain and shutter combination needed to be made. With the known luminance range that may be addressed by each gain and shutter combination, the accuracy of such combinations would enable researchers to determine appropriate manual configurations for the luminance camera system. This was done by applying the Slope Prediction of Luminance equation and making comparisons to known luminance data. Results of this are in table 5. Gain and shutter combinations containing saturated data are omitted.

Table 5. Percent of predicted luminance within 15% of actual luminance (by gain & shutter).

Gain (dB)	Shutter (ms)						
	6	11	16	21	26	31	36
0	87.5%	87.5%	96.3%	96.3%	97.5%	97.5%	96.3%
3	86.3%	93.8%	96.3%	96.3%	97.5%		
6	85.0%	91.3%	95.0%				
9	80.0%	95.0%					
12	86.3%						
15	88.8%						

These results indicate strong accuracy associated with shutter durations of 26 and 31ms, and a gain setting of 0dB. However, when this data is used with the results of table 4, one must take into account the range of luminance that may be accurately measured. Therefore, with a decrease in accuracy from a shutter of 26ms to 16ms, there is a tradeoff increase in measurable luminance from 32cd/m^2 to 47cd/m^2 (from table 5).

DISCUSSION

Results from the dynamic evaluation of the Luminance Camera indicate that more accurate results can be achieved with manually configured camera settings. The specific selection of such a configuration though is based on a consideration of multiple factors such as the accuracy of the prediction and the range of luminance that may be represented, and selections of gain and shutter configurations. For example, there may be instances when the researcher may require greater accuracy, while sacrificing range of luminance. However, in cases of a dynamic environment where a wide range of luminance will be encountered, the approach of a dual luminance camera system may be most appropriate. It is in these instances when both the higher and lower ranges of luminance may be addressed, while not sacrificing accuracy of such predictions.

CHAPTER 5. REPEATABILITY AND REPRODUCIBILITY

METHODOLOGY

Experimental Design

Following a static calibration of the luminance camera and the dynamic comparison of a manual configuration of camera settings to auto-enabled settings, an R&R (repeatability & reproducibility) evaluation was undertaken. The level of data consistency over time (repeatability) and among different users (reproducibility) is the purpose of the R&R evaluation. Results are presented based on the Automotive Industry Action Group (AIAG) satisfactory variance below 10 percent (AIAG, 2002).(3)

The evaluation of repeatability and reproducibility through the Gage R&R evaluation was conducted with select gain and shutter settings. The specific settings were based on results of the visibility of images from the dynamic evaluation and range of luminance being studied in the environment. The settings selected were a gain value of 6dB with a shutter of 11ms, as well as a gain of 21dB with a shutter of 21ms.

Three different users operated a vehicle equipped with cameras during this R&R evaluation. The environment was a pre-determined area to measure the consistency of data being collected by the cameras. Manipulated variables are shown in table 6. The variable number of drivers was important for the evaluation in order to understand if the camera system was obtaining reproducible data regardless of the driver of the vehicle. Dependent measures include average values of a wooden "pedestrian" cutout and a specific section of pavement.

Table 6. Independent variables - R&R evaluation.

Variable	Levels
Camera Setting	Gain = 6dB and Shutter = 11ms, Gain = 21dB and Shutter = 21ms
Drivers	Drivers 1,2,3

Equipment

Similar to the dynamic evaluation of Luminance Cameras, the vehicle used for this portion was the same 2002 Cadillac Escalade with cameras mounted beneath the rearview mirror of the vehicle

The environment captured during this evaluation is pictured below (figure 12). The location of the evaluation was a parking lot area without overhead lighting at the Virginia Tech Transportation Institute. A wooden "pedestrian" cutout and a section of designated pavement were the areas of interest. Multiple lasers were instrumented to the vehicle to assist with the orientation of the vehicle as well as to increase the consistency of the location of the vehicle. For example, lasers were attached to the vehicle so that laser-light emission would converge at a crosshair target in the evaluation area.

Figure 12. Photo. R&R evaluation area.

Procedure

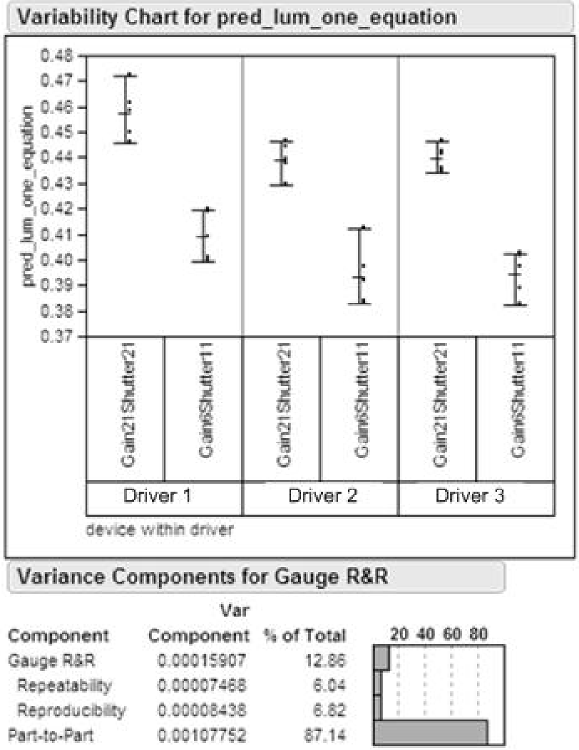
Three drivers were asked to position a luminance camera-equipped vehicle at a pre-determined location in the evaluation area. Drivers operated the same vehicle and rotated duty of driving. Driver #1 was asked to drive to the evaluation area and position the vehicle so two lasers equipped on the vehicle converged at crosshairs in the designated area. Images were then captured with two luminance cameras. Driver #1 was then asked to drive away from this location and return to attempt to reposition the vehicle at the same location. This was completed five times by each of the three drivers.

Data Analysis

The repeatability and reproducibility of the system (R&R) was also conducted. Results are presented based on the AIAG satisfactory variance below 10 percent (AIAG, 2002).(3)

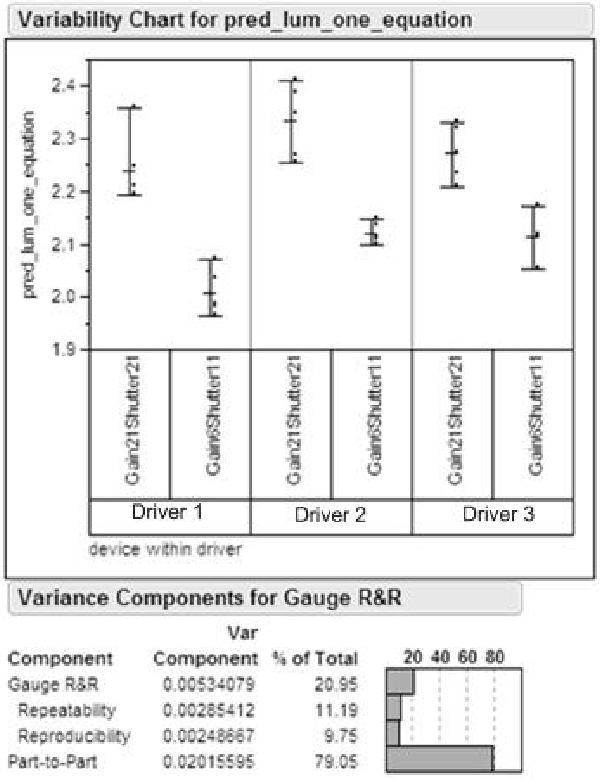
RESULTS

The results of the evaluation of the repeatability and reproducibility of the Luminance Camera system (figure 13 and figure 14) are below. The two reported areas of measurement were a rectangular shape of pavement designated by tape and a wooden pedestrian cut-out.



Component	Var Component	% of Total
Gauge R&R	0.00015907	12.86
Repeatability	0.00007468	6.04
Reproducibility	0.00008438	6.82
Part-to-Part	0.00107752	87.14

Figure 13. Diagram. Gage R&R result - pavement area.



Component	Var Component	% of Total
Gauge R&R	0.00534079	20.95
Repeatability	0.00285412	11.19
Reproducibility	0.00248667	9.75
Part-to-Part	0.02015595	79.05

Figure 14. Diagram. Gage R&R results - mean of "pedestrian."

As discussed earlier, three different drivers positioned the same vehicle at the same location in order to capture consistent images. Two devices, a camera set to gain 21db/shutter 21ms and a camera set to gain 6dB/shutter 11ms, were used. The results above indicate the consistency in device over time (repeatability) and among different users (reproducibility). Results indicate repeatability and reproducibility measurements of a designated area of pavement are 6.04 percent and 6.82 percent, respectively (figure 13). These values are the percent variation in the system resulting from the device and the operator (driver), respectively. The goal would therefore be to keep this percentage of variation at a minimal level. According to AIAG (2002)(3), a percentage of variation is considered "acceptable" below 10 percent, "may be acceptable" between 10 and 30 percent based on associated expenses and importance of application, and "unacceptable" above 30 percent. Therefore, these values would be considered acceptable.

Reproducibility measurements of a wooden pedestrian are also within the acceptable range, however results of the repeatability of the device lie beyond the 10 percent acceptable maximum. A possible explanation for this would be that the configuration of the camera evaluating the "lower" range of luminance (gain 21, shutter 21) approached a level of pixel saturation. This would result in inaccurate data for targets of higher luminance (above 2cd/m^2), but is appropriate for lower luminance values (below 2cd/m^2) such as the pavement area discussed above.

DISCUSSION

The R&R evaluation was found to be beneficial as it confirmed collection of data through the luminance camera system as repeatable and reproducible. Suggestions for future research into this type of evaluation would be the application of specific gain and shutter values not addressed, as well as a more realistic dynamic evaluation. For example, this would include the analysis of data from a moving vehicle rather than taking measurements from a stationary position.

CHAPTER 6. DYNAMIC ROADWAY COMPARISON

METHODOLOGY

Procedure

A comparison of the ProMetric photometer and the Luminance Camera was also conducted under dynamic conditions. This consisted of determining the mean luminance of targets selected along the roadway (such as pavement markings) through an analysis using the MATLAB programming software. This entailed the instrumentation of a vehicle with both the photometer and a Luminance Camera and driving to locations on public roads to capture images. Video images were continually taken with the Luminance Camera, and when the vehicle was parked, images were taken with the ProMetric photometer. The photometric images were then paired with the video Luminance Camera images that corresponded to the same moment in time. The luminance of targets, such as pavement markings, were then analyzed and compared.

Data Analysis

The analysis consisted of determining the mean luminance of targets selected along the roadway (such as pavement markings) through the use of the MATLAB programming software.

RESULTS

Examples of images captured through both the Luminance Camera and the ProMetric photometer are in figure 15 below.

Figure 15. Photo. Comparison of luminance camera (left) and ProMetric photometer (right).

Targets (such as pavement markings) were selected from images. The Slope-Based Prediction of Luminance was calculated for the Luminance Camera images. The mean luminance of such targets was determined for both the Luminance Camera images and the ProMetric images. The table below displays targets selected, the mean luminance and grayvalues associated with those targets, and the prediction of the luminance based on those grayvalues. The actual quotient of the photometer luminance and grayvalue is included in order to give an indication of what would have been a more appropriate Slope Calibration factor.

Table 7. Dynamic comparison results.

Target	ProMetric Photometer Luminance (cd/m^2)	Luminance Camera Grayvalue	Luminance Camera Predicted Luminance (cd/m^2)	Actual Quotient of ProMetric/ Luminance Camera Grayvalue
Mean of Pavement Marking for Bus Stop	1.0406	965.67	0.6263	0.0010
Mean of Stop Bar	2.508	2331	1.5118	0.0010
Bike Lane Shoulder next to curb	1.7892	2067.9	1.3412	0.0008
Mean of 1 Crosswalk Bar Left of Double Yellow	3.6644	3826.3	2.4817	0.0009
Mean of 1 Crosswalk Bar Right of Left Shoulder	5.2634	5530.3	3.5869	0.0009

As one can see from table 7, the predicted luminance based on the Slope Calibration developed from the calibration board consistently predicted a lesser luminance value than the values recorded by the photometer. The prediction is derived from the slope, therefore this leads one to consider that the slope generated from the calibration (m=0.000648) is too small of a value to use. As one can see from the right-most column in table 7, the value to be used should be in the area of 0.0009. A possible explanation for the low value would be the use of an inappropriate calibration control board or the lack of similarity between the incandescent light source used during calibration and the high pressure sodium headlamps used during the dynamic comparison.

In order to investigate the possibility of differences in calibration based on light source, the calibration was re-conducted with a 400-watt cobra-head high-pressure sodium (HPS) street luminaire in the same environment as the calibration. A sample of comparisons for the condition when the gain is at 0dB is displayed below.

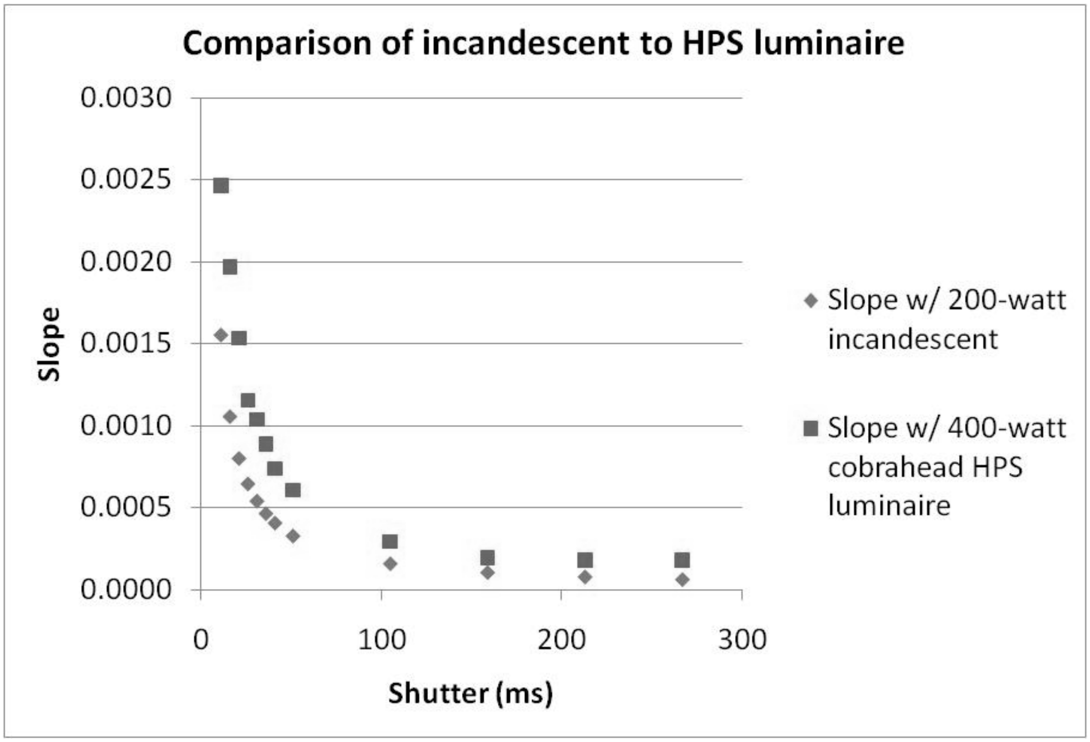


Figure 16. Graph. Calibration slopes for Gain = 0dB.

The results in figure 16 indicate a noticeable increase in resulting slope values as compared to the 200-watt incandescent bulb. Specifically, for the setting used for the dynamic comparison (gain = 0dB, shutter = 26ms), the resulting calibration slope was 0.0011. Coupled with the results of table 7, one can see how this value is a more appropriate calibration factor than the previously determined 0.0006. This leads to the consideration that the Luminance Camera system is impacted by the spectral distribution of the ambient lighting. Further research would entail an in-depth absolute calibration coupled with a spectraradiometer.

DISCUSSION

The dynamic comparison of the photometer and Luminance Camera indicate future areas of interest. The images were captured in a vehicle equipped with tungsten halogen headlamps as well as on roadways under high pressure sodium luminaires. Results indicate differences between the calibration factor developed through the static calibration procedure and the factor or slope that would have been more appropriate in the dynamic setting. However, with this in mind, the calibration process was then revised with a 400-watt HPS luminaire, similar to overhead roadway lighting. The results of the revision indicate the Luminance Camera calibration factor is influenced by the spectral distribution of ambient light. Future research prompts the consideration of a coupled spectraradiometer and Luminance Camera system to further investigate this.

This also suggested improvements that may be made in the area of the calibration process. An area prompting further research is the improvement of the calibration board and its location, in order to increase accuracy of the calibration. With adjustments to the board, such as a resurfacing with paint to allow a more consistent reflectance of light, the accuracy of the calibration model is expected to increase.

CHAPTER 7. CONCLUSIONS

The development of a dynamic method of measuring luminance was undertaken. Based on a photometer's known luminance output, a calibration of a digital video camera was achieved. The development of a rapid method of image capture for such a calibration was also accomplished. This will aid in future research associated with multiple cameras in the system as each camera will need individually specific calibration factors. The calibration of the Luminance Camera was found to be most accurate with the use of an equation based on each gain and shutter combination's respective slope. A single equation to predict luminance across any gain and shutter combination was found to be more flexible but less accurate in its ability to predict luminance. The recommendation is then the use of a specific calibration factor for each gain and shutter combination.

A working system for video capture in a dynamic setting was developed. The benefits of this include an increase in the amount of data that can be analyzed, as well as a more realistic analysis based on the natural dynamic nature of a naturalistic driving environment. The evaluation of multiple camera settings was undertaken, with the conclusion that manually determined camera settings of gain and shutter were optimal for accuracy of data collection. The specific settings are largely dependent upon the environment and targets of interest (e.g. pavement marking luminance vs. road signage luminance); however, there are suggestions for more general data collection.

An evaluation of the repeatability and reproducibility of data collection through the luminance camera system was successfully conducted. Results indicate that some variance in observed data may be attributed to the device or the driver with a Luminance Camera-equipped vehicle, but such variance is within acceptable limits.

A dynamic comparison of the luminance photometer and the developed Luminance Camera system was successfully undertaken. Results indicate the Luminance Camera as a feasible option for relative measurements of luminance, based on driving under high-pressure sodium overhead lighting. Further consideration must be made for its application with other types of light sources. Results also indicate possible improvements to the calibration procedure in order to increase accuracy.

Limitations

A limitation in the current research is the lack of user adjustments to luminance camera temperature. One of the benefits of the existing photometer is the presence of cooling capabilities in order to decrease the "noisy" pixels in an image. However, the luminance camera doesn't offer such a native capability. An effort in future research would be to design a cooler for dynamic data collection and make comparisons to existing predictions of luminance.

Another limitation involves the generation of the calibration models. While the models were developed using actual measured luminance from a photometer, the predictive strength of the models was evaluated against this same luminance. In essence, the models are predicting the very same luminance with which they were made. While the results indicate the models are accurate, future research of simultaneous photometric and luminance camera images would be required in order to confirm the accuracy of the luminance camera's predictive strength.

Improvements in the calibration procedure were also considered a limitation, as the light source being used may not accurately represent the lighting used by drivers or as overhead lighting. Further research would consist of multiple light sources, as well as the use of a full calibration board to allow a complete calibration across every individual pixel, to account for pixel variation across the board. A slope calibration factor specific to individual pixels, rather than a single value for a gain and shutter combination, may have provided more accurate predictions of luminance.

Finally, certain characteristics of the calibration board may be considered a limitation. The paint used for the board did not allow properly controlled reflectance to the photometer and Luminance Camera. While the cameras were positioned directly side-by-side, slight variations of the surface of the board will create varying intensities of light directed to the cameras for measurement. The location of the board is also currently housed in a garage used for other research purposes and studies. This was due to the lack of a more adequate facility for the calibration procedure. Improvements would be a repainted calibration board and relocation of this board to a facility solely dedicated to calibration procedures.

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