A new roadway lighting measurement system

Huaguo Zhou\textsuperscript{a,}\textsuperscript{*}, Fatih Pirinccioglu\textsuperscript{b}, Peter Hsu\textsuperscript{c}

\textsuperscript{a} Department of Civil Engineering, Southern Illinois University Edwardsville, Campus Box 1800, Edwardsville, IL 62026-1800, USA
\textsuperscript{b} Center for Urban Transportation Research, University of South Florida, 4202 E. Fowler Ave., CUT 100, Tampa, FL 33620, USA
\textsuperscript{c} Florida Department of Transportation, District 7, 11210 North McKinley Drive, Tampa, FL 33620, USA

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\textbf{A B S T R A C T}

Past studies have shown that the level of roadway lighting is an important factor for nighttime roadway safety. To evaluate roadway lighting systems and maintain their functionality, it is essential to perform field lighting measurements. Currently, field measurements of roadway lighting systems are often conducted by handheld light meters using a short sample section. The evaluation of an entire corridor or a longer section is difficult when using the traditional manual measurement methods. This paper addresses this difficulty by developing a new lighting measurement system that can be used to collect massive amounts of lighting level data in an efficient, safe, and effective manner. The system consists of a light meter, a distance measurement instrument (DMI), a computer, software, and an electronic converter circuit to connect the computer and other hardware. Software was developed for the communication link between the computer and the light meter, and to record both the distance and illuminance data. The system was calibrated and validated with the field data. The new system will not only reduce future data collection costs, but also improve safety for field data collection personnel. The system has been approved for use to collect illuminance data on Florida state roads greater than or equal to 250-miles in length.

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1. Introduction

Roadway lighting systems can be evaluated by three different methods: illuminance, luminance, and small target visibility. Among these methods, the illumination method is mostly used in the field evaluation of roadway lighting systems because the data can be acquired more easily than the other methods. Currently, roadway lighting illuminance levels are often measured with handheld light meters. After roadway lighting systems are designed, the design programs can establish a grid on the pavement surface and then use the illuminance values at these points on the grid to determine average values and uniformity ratios (avg/min and max/min). To manually collect illuminance data using handheld light meters on a regional scale represents an enormous data collection task. This data collection effort would also put the people operating the light meters in the middle of the roadways during nighttime low-lighting conditions, creating a safety concern for both data collection personnel and other roadway users.

In order to address these concerns, the authors developed a new measurement system for collecting lighting illuminance data in a manner that minimizes the risk exposure for data collection personnel. The idea is to measure lighting illuminance levels from a moving vehicle using a combination of a computer, a light meter, and a distance measurement instrument (DMI). The illuminance data recorded by a light meter will match the location data from the DMI.

\textsuperscript{*} Corresponding author. Tel.: +618 650 2815; fax: +618 650 2555.
E-mail address: hzhou@siue.edu (H. Zhou).

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With the new illuminance measurement system, Florida government traffic agencies will be able to evaluate lighting conditions along existing roads in their jurisdictions, and link highway lighting illuminance data to crash data to better identify the causes of nighttime crashes at high accident spots or segments. Locations that need lighting improvements can be prioritized and programmed.

The main objective of this research is to develop lighting measurement strategies that will help collect massive amounts of lighting level data in a rapid, safe, and effective manner. To achieve the main objective, the following tasks needed to be completed:

- develop a hardware system that collects the data automatically;
- develop a software system to collect and store data in a computer; and,
- test and calibrate the developed system.

2. Literature review

Roadway lighting is one of the key elements of a roadway system in regards to safety. Past studies (Walker and Roberts, 1976; Jones et al., 1980; Box, 1989; Road Lighting, 1992; Elvik, 1995; Bruneau et al., 2001; Elvik and Vaa, 2004) reveal that roadway lighting reduces the nighttime crash rate in a broad range (from 5% to 58%, for an average 35%). A Federal Highway Administration study (1990) reported that, in the United States, nighttime crash rates are five times greater than daytime crash rates. More to the point, approximately 50 percent of all fatalities occur during the nighttime even though only 25% of the total vehicle miles are driven during the nighttime. Siddiqui and Chu (2006) found that street lighting reduces the probability of fatal injuries by 42% at midblock location and by 54% at intersections. These results clearly indicate that improvements to the nighttime driving environment might reduce nighttime crash rates.

Little documentation has been found that addresses roadway lighting illuminance measurement. One study was found to develop a mobile illumination evaluation system by Zimmer (1988). The main purpose of the system was to collect illumination data for high mast lighting systems. High mast lighting is usually designed for freeways. It consists of an elongated vertical mast having upper and lower ends surrounded by an annular support ring of lamps. Illuminance measurements were taken by a light meter placed on the top of the test vehicle. The system could collect data at reasonable speeds. However, the technology for lighting measurements and computers at that time were not well developed. For high mast lighting systems, luminaires are mounted relatively higher than conventional roadway lighting. The measurements may be affected by the height of the light meter sensor as in conventional roadway lighting measurements. The study did not develop a methodology to convert the illuminance on the top of vehicles to six inches above the pavement as required by design guides (An Information Guide for Roadway Lighting, 2002; American National Standard Practice for Roadway Lighting, 1999). Meanwhile, a more recent study conducted by Zatari et al. (2004) presents a complex system in which a set of charge-coupled device (CCD) cameras was mounted on a test vehicle to obtain glare, luminance and illuminance measurements. The set of cameras required an infra-red and neutral density set of filters with an extensive calibration process. Also, the vehicle was equipped with a GPS, 3D orientation sensors, and image flow analysis system for accurate estimate the position of the vehicle. Another study conducted by Ekrrias et al. (2008) use a CCD camera to obtain luminance measurements. The luminance measures were based on the result of headlights simulation and road lighting analysis.

3. System development

Illuminance is one of the main criteria for the evaluation of roadway lighting conditions. Any illuminance measurement method requires measurement of illuminance (lux or foot candle) values at desired points. Collecting coordinates of desired points and corresponding illuminance data simultaneously and accurately is a challenging task. If coordinates and illuminance data were collected separately, it would be difficult to match them. Due to the above reasons, it was necessary to develop a measurement system that can collect both location and illumination data at the same time. After considering safety and speed issues, it was decided that the system should be installed on the top of a vehicle. The system installed on the top of a test vehicle could collect illumination data at a desired distance interval and at a reasonable speed of the test vehicle. In order to proceed to the design stage and identify necessary elements for the system, a system diagram was developed and provided as Fig. 1.

After the initial design, the project team determined the necessity of the following elements:

- light meter;
- distance measurement instrument (DMI);

![Fig. 1. System diagram and elements.](image-url)
• laptop computer;
• connections between the computer, light meter and DMI; and,
• software to collect, store, and analyze data.

3.1. Hardware

3.1.1. Light meter

A light meter is the main unit of the developed system. While in search of a suitable light meter for the system, it was found that there are many products available on the market. The selection of the light meter was based on the following five criteria:

• **Portable.** The system needs to be mobile and efficient. Portable light meters are preferred for mobility.
• **High accuracy.** High accuracy especially at low lighting levels is a necessity. The light meter must measure illumination levels of roadway lighting at desired accuracy. The accuracy levels of light meters usually come from the technical specifications of the manufacturers. For example, if precise illuminance at a point is 1 fc, a light meter with ±3% accuracy will measure the illuminance value from 0.97 to 1.03 fc at the same point. Most precise light meters on the market have ±2% accuracy.
• **Connection to computer.** Data collection and storage is conducted by using a computer. The selected light meter will be able to communicate with the computer.
• **Fast response time.** Data are collected in a moving vehicle with variable speeds. It is necessary for the light meter to respond quickly for changing environments and lighting levels.
• **Separate sensor.** The light meter’s sensor must be located outside of the vehicle during data collection. If the light meter has a separate sensor, the main unit of the light meter and connections to the light meter can be made from inside the vehicle while the exterior sensor is connected to the main unit. After comparing different light meters based on the above five criteria, Extech Instrument 401036 Model Light Meter was selected. The selected model has an accuracy of ±3% in measurement. For evaluation purpose, a ±5% would be the desired level. The sensor and main unit are two separate parts, and can be connected by an extendable cable. Additionally, the light meter has a built-in serial port to interface with a computer. The manufacturer also provided a computer communication protocol in the user manual. This protocol is used while developing the software for the system. The sampling time of the light meter is 2.5 readings per second, which permits taking measurements at distance intervals as short as 17.5 feet when the test vehicle travels at a speed of 30 mph.

3.1.2. Distance measurement instrument

An accurate measurement of the distance traveled by a test vehicle is critical for the system. Originally, two types of devices, a global positioning system (GPS) and a longitudinal DMI were considered for this component. However, portable GPS devices available on the market with reasonable prices have an accuracy of approximately 40 feet, which is not accurate enough for the system. In addition, the accuracy of a GPS device is affected by different factors such as weather (cloudy skies) and location (urban areas with high buildings).

A longitudinal DMI was chosen over a GPS device because of its higher accuracy (up to ±1 foot per mile) rate. The “RAC Plus II” from JAMAR Technologies, Inc. was selected between the three available devices on the market.

3.1.3. Computer

A laptop computer is an important part of the developed system. It was used not only for data collection and storage, but also to establish the communication link between the light meter and the DMI.

The selected light meter was produced with a built-in RS-232 (9-Pin) serial port and software for communication. The DMI has a distance pulse output (DPO) function, which can send digital low-current pulses at desired distance intervals to an electronic device. The light meter can be triggered if the pulses from the DMI are detected.

To make the light meter automatically measure the illuminance at the desired distance intervals, a circuit was designed to detect the pulse. Since a computer cannot detect a DMI pulse directly, the circuit sends the pulse to the computer in a form that the computer understands. The circuit was designed with a small microcontroller (PIC1684A). The microcontroller produced by Microchip Inc., was inexpensive and useful for this purpose. The circuit works as a filter and detects the pulse from the DMI and converts it into a serial communications format. A field test indicated that the circuit was successful in establishing the communication between the DMI and the light meter.

An issue with serial connections is that newer models of laptop computers do not come equipped with serial connection ports. The laptop computer used in this project only has one serial communication port. However, the developed system requires two ports. This issue was solved by using a “RS-232 to USB converter” device. This device and supported software creates a virtual serial port in one of the USB ports of the computer.

3.2. Software

Software is another important part of the developed system to ensure effective communications between the devices, as well as storage and analysis of the data. Microsoft Visual Basic was selected as the programming language because
communications with the computers serial ports are easy to control, and it is relatively easy to develop user interfaces with this programming language in comparison to other commercial products.

The initial step for developing software is to develop an algorithm. Algorithms can be illustrated through a flowchart in a graphical way. The flowchart of the developed software is shown in Fig. 2. After the software is tested and completed, a package is created to install the software in case the required library and control files used by the software are not present in the target computers.

4. Field test and system calibration

4.1. Field test

In order to test the functionality and accuracy of the Mobile Lighting Measurement System, field tests were conducted. First, the system was tested on the Tampa campus of the University of South Florida. Initial tests showed that the system works properly and data could be effectively collected at speeds of approximately 30 mph. After several successful on-campus road tests, field tests were then performed on a 2.5 mile segment of Fowler Avenue between 56th Street and I-75. Fowler Avenue is an eight-lane divided major arterial state road in Tampa, FL.

The lighting at this section consists of conventional and high mast lighting luminaires. The interchange area of Fowler Avenue and I-75 has high mast lighting systems installed. The remaining parts of the section were designed with conventional lighting systems. The illuminance values were measured in both the outside and inside lanes of each direction. Fig. 3 shows the illumination data collected at this segment in both lanes of the eastbound direction.
4.2. System calibration

Based on the FDOT lighting design guidelines (Plans Preparations Manual, 2007), illumination levels should be measured no more than six inches above the pavement surface. The lighting measurement system developed for this study can only measure the lighting level from the top of a vehicle. Therefore, a methodology needs to be developed to adjust the illumination value from the top of a vehicle to six inches above the ground. In order to accomplish this task, two separate measurements were taken: one at six inches above the ground and another at five feet and six inches above the road surface, which is the same height of a roof-mounted sensor of the light meter. After collecting the data, the relationship between the illumination measured from the top of a vehicle and six inches above the ground can be investigated.

A 1200 feet long roadway section including five luminaires was selected for system calibration. Illuminance data show great variance directly under luminaires. Grid points were placed along the lines parallel to the lane lines under luminaires. Grid points were separated at a distance of 20 feet from each other. Data were collected at 61 grid points for analysis. Fig. 4 shows illumination data versus distance.

From Fig. 4 it can be seen that illumination values between on top of vehicle and six inches above pavement significantly differ at the grid points which are close to the luminaires. However, the difference between the two values decreases as the distance from the point measured from the closest luminaire increases. From Fig. 4, it is not difficult to tell that two...
illuminance values at the different heights follow the same pattern. A conversion ratio can be calculated to convert the illuminance data measured from the top of the car to six inches above the pavement.

4.3. Inverse square method

Theoretically, the relationship between illumination and distance can be determined by the inverse square method (Lindsey, 1996). This method is used to calculate the illuminance value at a point if the luminous outputs and distance variables are known. Fig. 5 shows the required variables to utilize the inverse square method.

Where

\[
H_R = \text{Vertical distance between light source and road surface.}
\]

\[
H_S = \text{Vertical distance between light source and light meter sensor.}
\]

\[
S_h = \text{Vertical distance between road surface and light meter sensor.}
\]

\[
x = \text{Horizontal distance between light fixture and grid point in question in x direction.}
\]

\[
y = \text{Horizontal distance between light fixture and grid point in question in y direction.}
\]

\[
a = \text{Horizontal distance between light surface and point question } a = \sqrt{x^2 + y^2}.
\]

\[
D_R = \text{Distance between road surface and lighting fixture } D_R = \sqrt{H_R^2 + a^2}.
\]

\[
D_S = \text{Distance between light meter sensor and lighting fixture } D_S = \sqrt{H_S^2 + a^2}.
\]

\[
\gamma_R = \text{the angle from nadir of luminaire to the point on road surface.}
\]

\[
\gamma_S = \text{the angle from nadir of luminaire to the point at the height of light sensor.}
\]

By use of distance and luminous output variables, illuminance values can be calculated by Eqs. (1) and (2):

\[
E_{hr} = \frac{I \cdot \cos(\gamma_R)}{D_R^2}  \tag{1}
\]

\[
E_{hs} = \frac{I \cdot \cos(\gamma_S)}{D_S^2}  \tag{2}
\]

where

\[
E_{hr} = \text{Illumination level at road surface.}
\]

\[
E_{hs} = \text{Illumination level on top of the vehicle.}
\]

\[
I = \text{Luminous intensity of the luminaire.}
\]

When \( \gamma \) is replaced with \( H/D \) then Eq. (3) and (4) are obtained:

\[
E_{hs} = \frac{I \cdot H_R}{D_R^2}  \tag{3}
\]

\[
E_{hs} = \frac{I \cdot H_S}{D_S^2}  \tag{4}
\]
A ratio to adjust the measurements can be determined by dividing the illuminance value on the road surface to that at the height of the light meter sensor. Since $I$ is the same in Eqs. (3) and (4) when measurement are made at the same time and location, the illuminance above the pavement can be estimated using Eqs. (5) and (6).

$$\frac{E_{hR}}{E_{hS}} = \frac{H_R D_S^2}{D_H S^2}$$

$$E_{hR} = \frac{H_R D_S^2}{D_H S^2} E_{hS}$$

4.4. Multiple luminaires

All assumptions for the calculation of illuminance, up to this point, were made for one luminaire. However, the illumination value at a point on the road surface is usually the outcome of several luminaires. It is difficult to identify the contribution from different luminaires for every single measurement and to estimate the conversion ratio for each luminaire.

To examine the effects of horizontal distance on illuminance from a single luminaire, the inverse square method was used to calculate the illuminance for three different luminaire heights by assuming:

$I = 15000$ candela (cd);

luminaire height = 30, 35, and 40 feet; and,

light sensor height = 5.5 feet.

Figs. 6 and 7 show the trend of illuminance values and conversion ratios by distance for different luminaire heights. Based on Fig. 6, it can be concluded that the effect of a luminaire on the illumination value at a 200 feet distance away is negligible. In addition, Fig. 7 shows that ratios remain constant after 250 feet horizontal distance from the luminaires. The design spacing of light poles on most state roads is approximately 250 feet. The results in Figs. 6 and 7 indicate that the ratio can be determined by only considering the effects of two luminaries.

In order to determine conversion ratios with the effects of two luminaires, Eq. (5) can be used to calculate ratios from two luminaries, separately. Based on the distances of luminaires to the point measured, two ratios are added and the final ratio value can be determined. Fig. 8 shows all the variables for calculating the final ratio.

Where

$H_R$ = Height of luminaires from road surface.

$H_S$ = Height of luminaires from light meter sensor.

$D_{1S}$ = Actual distance between first luminaire and light meter sensor.

$D_{1R}$ = Actual distance between first luminaire and road surface on the line of light meter sensor.

$D_{2S}$ = Actual distance between second luminaire and light meter sensor.

$D_{2R}$ = Actual distance between second luminaire and road surface on the line of light meter sensor.

$S_h$ = Light meter sensor height when it is placed on the top of the vehicle.

![Variation of Illumination by Distance for I = 15000 cd](image)

Fig. 6. Variation of illumination value by distance.
Roadway lighting systems usually have constant luminaire height so we can assume that $H_1 = H_2 = H_R$ and $H_R - S_h = H_S$.

The following equations can be derived from Eqs. (3)–(5):

$$E_{hS} = E_{hS1} + E_{hS2}$$
$$E_{hR} = E_{hR1} + E_{hR2}$$
$$E_{hS} = \frac{H_S}{\mu_R} + \frac{H_R}{\mu_S}$$

Fig. (9) and field data shown in Fig. (4) are utilized to estimate the conversion ratios. Fig. (9) compares illumination values manually measured on the pavement surface and values calculated using the conversion ratios from the illumination values from the top of the vehicle.

The data collected on the road surface and the data obtained by utilizing conversion ratios have similar trends and the differences in values are small. A statistical test, however, could mathematically explain whether two data sets differ from each other significantly.

4.5. Statistical analysis

Fig. (10) shows the scatter plot for paired data values. The correlation ($R^2$) value between the two data sets is 0.99. This shows that the two data sets are strongly correlated; however, to determine if there is a significant difference between the two data sets, it is necessary to conduct a statistical test.
The paired t-test and the Wilcoxon test are commonly utilized to compare two paired data sets. One of the requirements for the paired t-test is that the data groups must have normal distributions. Meanwhile, the Wilcoxon test does not require normal distribution. To determine whether the distribution of data groups are normal or not, normality tests can be used. Additionally, frequency distribution plots can be used to determine the normality of data. Based on normality test results and visual inspections, the measured and converted data sets do not have a normal distribution. As a result, the Wilcoxon test was selected for the comparison of data. This test is a nonparametric alternative to a paired t-test.

The Wilcoxon test analyzes (Rees, 2001) the differences between the paired measurements. The P value (0.029) is used to determine whether the median difference really is zero overall. The hypotheses for the test are defined as:

\[ H_0: \text{The difference (d = measured - converted) between the members of each pair has a median significantly different from zero.} \]
\[ H_1: \text{The difference (d = measured - converted) between the members of each pair has a median value of zero. To be complete, measured and converted values have identical distributions.} \]

For a large enough sample size (n > 12), W has an approximately normal distribution, therefore its mean and variance are:

\[ \mu = \frac{n(n + 1)}{4} \tag{10} \]

---

**Fig. 9.** Comparisons of measured and converted illumination levels.

**Fig. 10.** Scatter Plot of the correlation between measured and converted illumination values.
where

\[ \mu = \text{Mean value} \]
\[ n = \text{Sample size} \]
\[ \sigma^2 = \frac{n(n+1)(2n+1)}{24} \]  \hspace{1cm} (11)

where

\[ \sigma^2 = \text{Variance} \]
\[ Z_W = \frac{W - \mu}{\sigma} \]  \hspace{1cm} (12)

where

\[ Z_W = \text{Test statistic} \]
\[ W = \text{Sum of the ranks} \]
\[ \mu = \text{Mean value} \]
\[ \sigma = \text{Variance} \]

Combining Eqs. (10)–(12), results in:

\[ Z_W = \frac{W - \frac{n(n+1)}{2}}{\sqrt{\frac{n(n+1)(2n+1)}{24}}} \]  \hspace{1cm} (13)

By completing the steps to compute \( W \) and using the equations, the following values are calculated:

\[ W = 1208 \]
\[ \mu = 945.5 \]
\[ \sigma = 139.2 \]
\[ Z_w = 1.89 \]

\( H_0 \) will be rejected in favor of \( H_1 \) if:

\[ Z_w > z_{a/2} \]

For the 95% confidence level and one tailed test:

\[ z_{a/2} = 1.645 < Z_w = 1.89 \]

Based on the results of this test, we can conclude that the null hypothesis is rejected in favor of \( H_1 \) and the median of differences for measured and converted values are not significantly different from zero at the 95% confidence level.

5. Summary and conclusions

The traditional lighting measurement method with a handheld light meter creates potential safety concerns for both data collection personnel and other roadway users, and it is labor-intensive. This study focused on developing a new lighting measurement method that can be used to collect lighting level data efficiently and in a safe manner. The following conclusions were reached as a result of this study:

- The methodology for developing the new mobile lighting measurement system was based on the illuminance method because: (1) standards and earlier studies indicated that the illuminance method is mostly used in field evaluations of roadway lighting systems; (2) data can be acquired easier than other methods and, (3) safety can be improved by illumination design approach.
- A new mobile measurement system was developed to collect both distance and illumination data simultaneously at some desired points. The system consisted of a light meter, a DMI, a computer, software, and connections for system elements.
- The light meter used can measure two and half readings per second. At the speed of 30 mph, the system could collect illumination data at 17.5 feet intervals.
- Inverse square method was used to determine ratios to convert the measurements from the top of the test vehicle to measurements on the road surface.
- Wilcoxon test was utilized to compare the illuminance measured above the pavement and from the top of the vehicle. Based on the test results, it was concluded that the median of differences for measured and converted values are not significantly different from zero.
In conclusion, the new lighting measurement system developed by this research can be used to safely collect massive light data in short periods of time. The new system will not only reduce the cost of future data collection efforts, but it will also improve safety for data collection personnel.

Future work will be performed to collect lighting intensity level using the system on 245 miles of state roadways in FDOT District 7. The lighting intensity level collected will be integrated into an existing GIS-based crash database maintained by FDOT to conduct a statistical analysis to evaluate the relationship between the illuminance levels and the night time crashes.

References


