The Effects of Roadway Lighting Levels on Traffic and Pedestrian Safety

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Executive Summary

The lighting data on 245 mile roadway were collected for this study. A new method and a set of new criteria were developed to evaluate performance of the roadway lighting system at corridor level with this new data collection technique.

A series of statistical analyses were conducted on the collected roadway lighting data and an empirical roadway illuminance intensity distribution model was established. The global performance of the roadway lighting system can be measured by the mean and standard deviation of the illuminance intensity distribution and the roadway evaluation criteria based on these two parameters were established. This method was used to evaluate the global performance of the 245 centerline miles of roadway lighting system at corridor level.

To justify the proposed roadway illuminance intensity evaluation method, the relationship between the roadway lighting performance and the traffic safety performance during nighttime was analyzed. Results indicated that both the standard deviation and mean of the illuminance intensity distribution are correlated with the safety performance of the roadway system during nighttime.
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INTRODUCTION

Proper design and timely maintenance are two vital factors for street lighting systems to be effective and beneficial to road users. The design itself needs to consider many factors and requires expertise in many areas, such as civil, electrical, and lighting engineering. The newly installed system should be evaluated to assure that roadway lighting levels meet the design standards. Initial design might be perfect. However, as time passes, the system may not work as well as when initially installed. In order to maintain the effectiveness and functionality of street lighting systems after design, they should be inspected to assess how well the system is being maintained.

Theoretically, roadway lighting systems can be evaluated by three different methods: illuminance, luminance, and small target visibility. Among these methods, the illuminance method is mostly used in the field evaluation of roadway lighting systems because the data can be acquired easier than the other methods. This method requires measurement of illuminance values at desired points on the road surface.

Illuminance is defined as the amount of light flux that falls on the surface at a certain distance from the light source. The standard units of illuminance used in practice are foot candle (English) and lux (Metric). The surface under consideration for illuminance determination in roadway lighting is the pavement surface. Horizontal illuminance is used in the standard practice of roadway lighting design and evaluation.

Evaluation of roadway lighting systems is an important task to ensure that the system works at the desired level. Evaluation methodology is usually selected based on the standards required for the lighting system. The timing of the evaluation is another factor to take into consideration. Current evaluation methods are designed for a newly installed lighting system. They are seldom used for evaluation of an existing lighting system at the corridor level because of the huge labor-intensive data collection effort. It also dangerously exposes the data collectors to the nighttime driving environment.

To solve this problem, a mobile lighting measurement system was developed to collect the illuminance data in a more efficient and safer way. This system was used to successfully collect illuminance measurements on approximately 245 centerline miles of state road in central Florida. The lighting data were collected every 40 ft on the inside and outside lanes in both directions. The criteria for newly designed lighting systems cannot be applied to evaluate the lighting system when the lighting data was collected with this method. Therefore, a new method needs to be developed to evaluate the roadway lighting system with this new data collection method.

A pilot study showed that the majority of nighttime pedestrian crashes happen
on roadway segments with low lighting levels. However, the impact of roadway lighting conditions on nighttime safety performance hasn’t been quantified yet. The relationship between nighttime crash rates and lighting system performance could be used to establish the evaluation criteria for the new data collection method.

This study is to evaluate the lighting system performance at a corridor level with its global illuminance intensity characteristics. A set of evaluation criterion for the new lighting data collection method will be developed accordingly. The relationship between nighttime crash rates and global lighting system performance will also be quantified. This research is based on the data collected in previous research projects funded by the Florida Department of Transportation (FDOT) District 7.

OBJECTIVES

The main objective of this paper is to develop a new method to evaluate an existing roadway lighting system at a macroscopic level and correlate lighting levels with nighttime crashes. The objectives were achieved with the following two steps.

The first step is to determine the distribution of illuminance intensity along a corridor. The lighting data collected every 40 ft on the outside and inside lanes for each direction were combined together to see whether a theoretical model could be developed to fit its distribution. When justified, the model parameters determined with the collected lighting data can be used to describe the global performance of the lighting system, and the lighting criteria expressed in the form of the distribution parameters can also be used to evaluate the lighting system directly.

The second step is to correlate nighttime crashes with the global lighting system performance. The lighting conditions are assumed to be a significant difference in the roadway system between daytime and nighttime. A regression analysis between the nighttime crash rate and the global lighting system performance, such as mean and variance of the illuminance intensity, was conducted.

LITERATURE REVIEW

Evaluation of Lighting System

In the literature review, many guidelines were found for the design of roadway lighting systems. However, few guidelines and standards are available for evaluation purposes.

AASHTO Roadway Lighting Design Guide (5) recommends three methods
for evaluation of pavement luminance and veiling luminance of the system: (1) Direct Measurement with Luminance Instrument, (2) Measurement of Incident Light, and (3) Calculation from Photometered Luminaires. For the second method: Measurement of Incident Light, it states “After the installation of the system, incident light levels (illuminance) are measured at each grid point and compared to the predicted values. Predicted values can be obtained from the design software. One advantage of this method is that the results will not be affected by the type of pavement. This method can also reveal the problems related to the luminaries, such as improper location and light source output.”

IESNA Guide for Photometric Measurements of Roadway Lighting Installations provides a step by step procedure for the field measurement of illuminance and luminance levels on roadways. For illuminance measurements, it states “Before starting field measurements, the roadway can be marked off in longitudinal and transverse roadway lines. Transverse lines are at a quarter lane width distance from the lane lines. Longitudinal points must be no more than 16.5 feet away from each other. There should be at least ten points between two luminaires. Horizontal illuminance readings are taken at each grid point and these readings are used to calculate average, maximum and minimum values, and system ratios which are the ratios of average to minimum and maximum to minimum. Moreover, additional readings can be taken under the luminaire and at the middle point of two luminaires to obtain maximum and minimum values. The location of the sensor should not be more than six inches above the road surface.”

The above two methods are often used to evaluate illuminance level for a newly installed street lighting. It is not designed to evaluate the existing lighting system at a corridor level.

Impacts of Roadway Lighting on Nighttime Crashes

Roadway lighting is one of the key elements of a roadway system in regards to safety. Past studies reveal that roadway lighting reduces the nighttime crash rate in a broad range (from 5 to 58 percent, for an average 35%). A Federal Highway Administration study 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 percent of the total vehicle miles are driven during the nighttime. Siddiqui et. al. found that street lighting reduces the probability of fatal injuries by 42% at midblock location and by 54% at intersections. A study conducted by Green et al. at the Kentucky Transportation Center of the University of Kentucky, indicated that nighttime crashes were reduced by 45 percent after installing street lighting at the intersections. These results clearly indicate that improvements to the nighttime driving environment might reduce nighttime crash rates. However, few documents were found to investigate the detailed
correlation between the illuminance levels and night time crashes. There is no any regression analysis that has proved that the lighting intensity level is the factor that affects crash frequency/rates at a statistically significance level.

**METHODOLOGY**

**Corridor-Level Illuminance Distribution Model**

*Log-normal Distribution*

A variable \( X \) is lognormal distributed if \( \ln(X) \) is normally distributed. The general formula for the probability density function of the Log-normal distribution is

\[
f(x; \mu, \sigma) = \frac{1}{x \sigma \sqrt{2\pi}} e^{-\frac{(\ln(x) - \mu)^2}{2\sigma^2}}
\]  

(1)

where \( \mu \) and \( \sigma \) are the mean and standard deviation of \( \ln(X) \). For Log-normal distribution, its mean and variance are as following:

\[
E(X) = e^{\mu + \frac{\sigma^2}{2}}
\]  

(2)

\[
Var(X) = (e^{\sigma^2} - 1)e^{2\mu + \sigma^2}
\]  

(3)

A variable might be modeled as Log-normal if it can be expressed as the multiplicative product of many independent random variables each of which is positive.

**Empirical Illuminance Distribution Model**

Theoretically, the illuminance intensity value varies continuously along the two lighting poles. For this study, however, the lighting data were collected discretely along the corridors every 40 ft on the outside and inside lanes at both directions. At corridor level the distance from every data collection point to the nearest lighting post could be treated as randomly distributed. Accordingly, the illuminance intensity values at corridor level could be treated as random variables as well. Hopefully, its distribution model could be identified with an established distribution model and only parameters of the distribution model are needed to describe the performance of the lighting system at corridor level.
The distribution of illuminance intensity was established with the following empirical method. For description convenience, the illuminance intensity value and its natural logarithm were denoted as X and LN(X) in the following contexts. It was observed that for roadways with uniform lighting condition the illuminance intensity value (X) at corridor levels belong to the Log-normal distribution. That is to say, the natural logarithm of the illuminance intensity value (LN(X)) belongs to the Normal distribution. For each corridor, the normality of LN(X) was tested with the Anderson-Darling method. If the normality of LN(X) could be justified, the illuminance intensity value could be modeled with Log-normal distribution. Only the mean and variance of LN(X), \( \mu \) and \( \sigma^2 \), will be needed to describe the global lighting performance at the corridor level.

*Evaluating Lighting System at Corridor Levels*

The average illuminance level and uniformity ratio were the criteria adopted in the lighting design standard. Based on the Log-normal distribution assumption, the mean and variance of LN(X), \( \mu \) and \( \sigma^2 \), were used to substitute the lighting criteria of average illuminance level and uniformity ratio, and new criteria were developed in the form of \( \mu \) and \( \sigma^2 \) to help evaluate the performance of the lighting systems at corridor level directly.

*Nighttime Crashes and Lighting Level*

In this study, the lighting condition was assumed to be the only major difference of the roadway system between daytime and nighttime.

All the crashes that occurred on the designated roadways from Year 2005 to 2007 were extracted from the Florida CARS (Crash Analysis Reporting System) database. The lighting condition variable in the database was used to separate the daytime and nighttime crashes. The daytime and nighttime crash rates were calculated based on the corridor length, number of crashes and AADT during daytime and nighttime respectively. The difference between daytime and nighttime crash rates is the dependent variable.

The Log-normal model was selected to describe the distribution of illuminance intensity at the corridor level. For each corridor, the distribution parameters \( \mu \) and \( \sigma \) were calculated based on the collected lighting data, and the mean and variance of the illuminance intensity, E(X) and Var(X), were calculated accordingly. The E(X) and
Var(X) are the two independent variables that were defined to reflect the performance of the lighting system at corridor level.

A regression analysis was conducted to see whether a significant relationship exists between the crash rate difference and the mean and variance of the illuminance intensity at corridor level. To show the impact of E(X) and Var(X) independently, the database was grouped based on the E(X) and Var(X) values respectively.

DATA COLLECTION

Existing Street Lighting Data

A total of 37 corridors were selected for illuminance measurement, as shown in Table 1. Most of these corridors had low lighting levels and high percentage of nighttime crashes. The illuminance data were measured every 40 ft on the right (outside) side and left (inside) side lane for each direction of the roadway and saved separately. The 37 roadway corridors were further divided into 77 corridors where uniform lighting performance could be achieved.

Figure 1 shows one of the corridors selected for the study, a six-lane divided highway with lighting poles on both sides. The top left corner of Figure 1 shows the box that contains the Distance Measurement Instrument (DMI). The bottom right picture shows the sensor of a light meter on top of the vehicle. The four red arrows showed the inside and outside lanes where the illuminance data were measured.
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<td>Gulf Blvd.</td>
<td>0.000</td>
<td>6.752</td>
<td>6.752</td>
<td>SR 666</td>
<td>Walsingham Road</td>
</tr>
<tr>
<td>36</td>
<td>15150000</td>
<td>US 19</td>
<td>0.867</td>
<td>31.829</td>
<td>30.962</td>
<td>54th Ave. S</td>
<td>Live Oak St.</td>
</tr>
<tr>
<td>37</td>
<td>15240000</td>
<td>Gandy Blvd./4th St.</td>
<td>0.000</td>
<td>8.883</td>
<td>8.883</td>
<td>US 19</td>
<td>I-275</td>
</tr>
</tbody>
</table>
Figure 1 Example of Segment for Data Collection

Figure 2 shows the illuminance levels measured on a one-mile corridor. The color change illustrates the change in the illuminance level along the corridor. For this particular corridor, the data were collected for the inside and outside lanes at each traffic direction. The illuminance measurements were automatically matched with the corresponding milepost data obtained by the DMI unit.

Figure 2 An Example of Illuminance Data Measured on one-mile segment

Existing Crash Data
Daytime crash and Nighttime Crash

The crash data for the 245 miles of state roadways from 2005 to 2007 were extracted from the FDOT CARS (Crash Analysis Reporting System) database. The lighting condition variable was used to classify the daytime and nighttime crashes. Crashes with lighting condition being “dark (street light)” or “dark (no street light)” were classified as nighttime crashes, and crashes with lighting condition being “daylight”, “dusk” or “dawn” were classified as daytime crashes. Crashes with lighting condition being “unknown” were further investigated based on the exact date and time of the crashes.

Altogether 32,159 crashes occurred from year 2005 to 2007, among which 24,559 were daytime crashes and 7,600 were nighttime crashes. The numbers of daytime and nighttime crashes were counted at corridor levels, separately.

Corridor AADT

The AADTs in the FTI (Florida Traffic Information) database were provided at segment levels. The corridor AADT was calculated as a weighted average value of the segment AADTs, as shown below:

$$AADT = \frac{\sum l_i AADT_i}{\sum l_i}$$ (4)

in which $l_i$ is the length of segment $i$, and $AADT_i$ is the AADT of segment $i$. The percentages of AADT during nighttime, $P_N$, were determined with the 48-hour traffic counts in the FTI database.

Daytime and Nighttime Crash Rate

The daytime and nighttime crash rates at corridor level, $CR_N$ and $CR_D$, were defined as following:

$$CR_N = \frac{N_i}{AADT \times P_N \times L \times 10^6} \times 10^6$$ (5)

$$CR_D = \frac{D_i}{AADT \times (1 - P_N) \times L \times 10^6} \times 10^6$$ (6)
where, \( N_i \) and \( D_i \) are the number of daytime and nighttime crashes from year 2005 to 2007 on corridor \( i \), \( L_i \) is the length of corridor \( i \), \( AADT_i \) is the AADT on corridor \( i \), and \( P_{N_i} \) is the percentage of AADT during nighttime for corridor \( i \). The units of \( CR_N \) and \( CR_D \) are number of crashes per million vehicle mile travelled. For each roadway segment the daytime and nighttime crash rates were calculated and listed in Table 2.

Two parameters, RD and RP, were defined to reflect the difference between the crash rates during nighttime and daytime. RD was defined as the difference between nighttime and daytime crash rate, and RP was defined as the relative increase of nighttime crash rate as compared with that of daytime, as shown below.

\[
RD = CR_N - CR_D
\]  
\[RP = \frac{CR_N - CR_D}{CR_D} \times 100\%\]

![Figure 3 Relationship between RD and RP](image)

In this study, the RD values were found to be proportional to the RP values, as shown in Figure 3. Only RD will be used to analyze the relationship between the lighting level and crash rate difference.
<table>
<thead>
<tr>
<th>Roadway ID</th>
<th>Length (mile)</th>
<th>Number of Crashes in 3 years</th>
<th>AADT</th>
<th>Crash Rate (Million Vehicle Mileage Travelled)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Daytime</td>
<td>Nighttime</td>
<td>Daytime</td>
</tr>
<tr>
<td>02010000</td>
<td>0.962</td>
<td>36</td>
<td>8</td>
<td>29,203</td>
</tr>
<tr>
<td>02030000</td>
<td>3.402</td>
<td>158</td>
<td>28</td>
<td>22,502</td>
</tr>
<tr>
<td>08010000</td>
<td>0.788</td>
<td>10</td>
<td>3</td>
<td>9,586</td>
</tr>
<tr>
<td>10005000</td>
<td>2.864</td>
<td>229</td>
<td>67</td>
<td>17,930</td>
</tr>
<tr>
<td>10020000</td>
<td>8.257</td>
<td>997</td>
<td>213</td>
<td>24,948</td>
</tr>
<tr>
<td>10020000</td>
<td>2.947</td>
<td>298</td>
<td>101</td>
<td>13,115</td>
</tr>
<tr>
<td>10030000</td>
<td>4.763</td>
<td>950</td>
<td>291</td>
<td>40,698</td>
</tr>
<tr>
<td>10030000</td>
<td>2.462</td>
<td>73</td>
<td>35</td>
<td>9,232</td>
</tr>
<tr>
<td>10030101</td>
<td>1.788</td>
<td>42</td>
<td>10</td>
<td>8,650</td>
</tr>
<tr>
<td>10040000</td>
<td>8.182</td>
<td>1,220</td>
<td>360</td>
<td>20,219</td>
</tr>
<tr>
<td>10060000</td>
<td>12.114</td>
<td>473</td>
<td>179</td>
<td>20,053</td>
</tr>
<tr>
<td>10080000</td>
<td>1.765</td>
<td>234</td>
<td>81</td>
<td>38,052</td>
</tr>
<tr>
<td>10110000</td>
<td>6.970</td>
<td>770</td>
<td>228</td>
<td>42,425</td>
</tr>
<tr>
<td>10130000</td>
<td>3.515</td>
<td>640</td>
<td>191</td>
<td>68,254</td>
</tr>
<tr>
<td>10140000</td>
<td>5.530</td>
<td>159</td>
<td>73</td>
<td>49,000</td>
</tr>
<tr>
<td>10150000</td>
<td>7.803</td>
<td>1,721</td>
<td>592</td>
<td>60,664</td>
</tr>
<tr>
<td>10160000</td>
<td>9.583</td>
<td>2,009</td>
<td>557</td>
<td>62,507</td>
</tr>
<tr>
<td>10250000</td>
<td>0.992</td>
<td>167</td>
<td>75</td>
<td>12,900</td>
</tr>
<tr>
<td>10250101</td>
<td>1.098</td>
<td>211</td>
<td>115</td>
<td>11,008</td>
</tr>
<tr>
<td>10270000</td>
<td>2.000</td>
<td>308</td>
<td>95</td>
<td>42,500</td>
</tr>
<tr>
<td>10290000</td>
<td>5.977</td>
<td>1,232</td>
<td>342</td>
<td>57,404</td>
</tr>
<tr>
<td>10310000</td>
<td>3.530</td>
<td>566</td>
<td>173</td>
<td>41,922</td>
</tr>
<tr>
<td>10330000</td>
<td>6.023</td>
<td>829</td>
<td>199</td>
<td>33,017</td>
</tr>
<tr>
<td>14030000</td>
<td>12.447</td>
<td>2,462</td>
<td>795</td>
<td>58,117</td>
</tr>
<tr>
<td>15007000</td>
<td>3.061</td>
<td>230</td>
<td>85</td>
<td>33,025</td>
</tr>
<tr>
<td>15010000</td>
<td>12.493</td>
<td>1,204</td>
<td>293</td>
<td>35,308</td>
</tr>
<tr>
<td>15030000</td>
<td>6.841</td>
<td>764</td>
<td>244</td>
<td>52,720</td>
</tr>
<tr>
<td>15040000</td>
<td>4.773</td>
<td>566</td>
<td>249</td>
<td>47,958</td>
</tr>
<tr>
<td>15110000</td>
<td>1.773</td>
<td>220</td>
<td>33</td>
<td>28,942</td>
</tr>
<tr>
<td>15120000</td>
<td>12.295</td>
<td>1,598</td>
<td>489</td>
<td>42,323</td>
</tr>
<tr>
<td>15150000</td>
<td>30.962</td>
<td>4,183</td>
<td>1396</td>
<td>58,140</td>
</tr>
</tbody>
</table>
DATA ANALYSIS

Lighting Data Distribution

Empirical Distribution of Corridor-level Illuminance Intensity

As can be seen from the figures in the Appendix, for most corridors, their illuminance intensity distributions were similar with Log-normal distribution, as shown in Figure 4. To testify whether the illuminance intensity (X) at a corridor level belongs to the Log-normal distribution, the normality of the natural logarithm of illuminance intensity (LN(X)) was tested firstly. Based on the relationship between Normal and Log-normal distribution, if LN(X) belongs to the Normal distribution, X will belong to the Log-normal distribution.

![Probability Distribution Function of Illuminance X](image)

**Figure 4 Distribution of Illuminance Intensity at a Corridor Level**

Normality Test

The Anderson-Darling method was used to test the normality of LN(X). The normality test results indicated that for 83% corridors the P-value is greater than 0.005. The normality test figure also showed that most points fall on the same straight line, as shown in Figure 5. The mean and variance of LN(X) were also calculated.
simultaneously with the collected lighting data.

Based on the normality test results, it’s concluded that the illuminance intensity data collected using the mobile lighting measure system at a corridor level belongs to the Log-normal distribution.

**Mean and Variance of the Distribution of Illuminance Intensity at Corridor Levels**

The mean and variance of illuminance intensity, E(X) and Var(X), were calculated with Equation (2) and (3). For the selected corridors E(X) ranged from 0.017 to 4, and Var(X) ranged from 0.0002 to 35. The E(X) and Var(X) were found to be correlated significantly and a power function was used to model their relationship, as shown in Figure 6. With the increase of the mean illuminance intensity, the variance will increase correspondingly.
Optimal Lighting Distribution

The average illuminance level and uniformity ratio were the two main evaluation criteria in the lighting design standard. Table 3 is the lighting criteria for different roadway classifications in the Florida Department of Transportation’s (FDOT) “Plans Preparation Manual”.

<table>
<thead>
<tr>
<th>Roadway Classifications</th>
<th>Illumination Level Average Initial (H.F.C.)</th>
<th>Uniformity Ratios</th>
<th>Avg./Min.</th>
<th>Max./Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interstate, expressway, freeways &amp; major arterials</td>
<td>1.5</td>
<td></td>
<td>4:1 or less</td>
<td>10:1 or less</td>
</tr>
<tr>
<td>All other roadways</td>
<td>1.0</td>
<td></td>
<td>4:1 or less</td>
<td>10:1 or less</td>
</tr>
<tr>
<td>Pedestrian ways and bicycle lanes</td>
<td>2.5</td>
<td></td>
<td>4:1 or less</td>
<td>10:1 or less</td>
</tr>
</tbody>
</table>

The illuminance intensity at a corridor level was tested to be the Log-normal distribution. The distribution parameters $\mu$ and $\sigma$ can be used to replace the average illumination level and uniformity ratios to see if these two criteria meet the standard requirements. To evaluate the lighting system at corridor level, $\mu$ and $\sigma$ of Log-normal distribution can be used the same as average illuminance level and uniformity ratio in Table 2.

The average, minimum and maximum illuminance intensity values under the Log-normal distribution assumption were determined firstly. For normal distribution
with parameters $\mu$ and $\sigma$, 95% of values fall into the range of $[\mu - 2\sigma, \mu + 2\sigma]$. That is to say, at the confidence level of 95%, the random variable lies between $\mu + 2\sigma$ and $\mu - 2\sigma$. In other words, at the confidence level of 95%, the maximum and minimum values observed are $\mu - 2\sigma$ and $\mu + 2\sigma$ respectively. Since $e^x$ is a monotone function, it’s reasonable to assume that the maximum and minimum values observed in the Log-normal distribution are $e^{\mu-2\sigma}$ and $e^{\mu+2\sigma}$ with a high confidence level. The average illuminance level was substituted with the mean illuminance intensity $e^{\mu+\frac{\sigma^2}{2}}$ directly.

The lighting criteria could be established in the form of $\mu$ and $\sigma$ accordingly. For major arterials, which are exactly the roadway classification under investigation, the lighting criteria are as following:

$$
\begin{align*}
1 & \leq e^{\frac{\sigma^2}{2}} \leq 4 \\
1 & \leq e^{\sigma} \leq 10 \\
\sigma^{\mu+2\sigma} & \geq 1.5
\end{align*}
$$

That is, $\sigma \in [0, \frac{\ln 10}{4}]$ and $\mu \geq \ln 1.5 - \frac{\sigma^2}{2}$, as shown in Figure 7. For other roadway classifications, similar criteria could be set as well.

Figure 7 shows the three areas: area under average illumination level, area under minimum uniformity ratio, and area above the standard levels for both average and uniformity ratio. This figure can be used to evaluate the lighting system when lighting data collected at corridor levels are available. To meet the lighting criteria, the $\mu$ and $\sigma$ values should fall into the area by the solid red lines.
Illuminance Intensity and Crashes

The average illuminance level and uniformity ratio are the two criteria in lighting design standard. In this paper, the mean and variance of illuminance intensity, \( E(X) \) and \( \text{Var}(X) \), were used to reflect the lighting level at a corridor level.

Mean Illuminance Intensity and RD

The \( \text{Var}(X) \) for the selected corridors ranged from 0.0002 to 35. To evaluate the influence of mean illuminance intensity (denoted as MII below) on RD independently, the dataset was divided into 7 groups based on the values of illuminance intensity variance (denoted as IIV below) and a power function model was used in the regression analysis. The IIV range, regression function parameters and R-square value for each group were listed in Table 4.
Table 4 Regression Model for Different Illuminance Intensity Variance

<table>
<thead>
<tr>
<th>Group Number</th>
<th>Variance Range</th>
<th>Regression Function</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0,0.1)</td>
<td>$RD = 0.3057MII^{-0.8}$</td>
<td>0.4111</td>
</tr>
<tr>
<td>2</td>
<td>(0.1,0.5)</td>
<td>$RD = 0.7984MII^{-0.726}$</td>
<td>0.4117</td>
</tr>
<tr>
<td>3</td>
<td>(0.5,1.0)</td>
<td>$RD = 1.2887MII^{-1.304}$</td>
<td>0.4389</td>
</tr>
<tr>
<td>4</td>
<td>(1.0,2.0)</td>
<td>$RD = 2.8448MII^{-1.021}$</td>
<td>0.4632</td>
</tr>
<tr>
<td>5</td>
<td>(2.0,2.5)</td>
<td>$RD = 5.2922MII^{-1.559}$</td>
<td>0.6979</td>
</tr>
<tr>
<td>6</td>
<td>(2.5,+$\infty$)</td>
<td>$RD = 3.4031MII^{-1.976}$</td>
<td>0.6804</td>
</tr>
<tr>
<td>7</td>
<td>(3.0,+$\infty$)</td>
<td>$RD = 4.3087MII^{-2.274}$</td>
<td>0.7556</td>
</tr>
</tbody>
</table>

Figure 8 Relationship between Mean Illuminance Intensity (MII) and RD

The relationship between RD and MII was plotted in Figure 8. The following tendencies could be observed based on the regression results and the above figure:

1. There is a power function relationship between the MII and RD. The R-square values lie between 0.4111 and 0.7556;
2. During each IIV group, the RD value decreases with increases on MII. Within the same IIV group, less nighttime crashes occur on roadways that have lighting systems with higher MII values;
(3) For the same MMI value, in most case the RD value increases when the IIV value increases. Roadways with better uniformity will have less crashes when MMI is the same;

(4) For the 7 different groups, the RD reduced 42.6%, 39.5%, 59.5%, 50.7%, 65.6%, 74.6%, 79.3% respectively when MMI increased from 1.0 to 2.0;

(5) The RD is close to 0 when MMI is approximating positive infinite; and

(6) For all the groups the RD varied dramatically at low MMI values while almost remained constant for high MMI values;

Illuminance Intensity Variance and RD

The relationship between IIV and RD was also examined. The MMI ranged from 0.017 to 4. To find the impact of IIV on RD independently, the dataset was divided into 5 groups based on the MMI values. Corridors with similar MMI values were grouped together. For each group, a linear regression function was used to model the relationship between IIV and RD, as shown in Table 5.

<table>
<thead>
<tr>
<th>Group Number</th>
<th>Range of Mean</th>
<th>Regression Function</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(0,0.1)</td>
<td>$RD = 219.99IIV + 0.7438$</td>
<td>0.5879</td>
</tr>
<tr>
<td>2</td>
<td>(0.1,0.5)</td>
<td>$RD = 19.132IIV + 0.4383$</td>
<td>0.7513</td>
</tr>
<tr>
<td>3</td>
<td>(0.5,0.75)</td>
<td>$RD = 4.5756IIV - 0.5015$</td>
<td>0.6467</td>
</tr>
<tr>
<td>4</td>
<td>(0.75,1.5)</td>
<td>$RD = 1.0798IIV + 0.2598$</td>
<td>0.5432</td>
</tr>
<tr>
<td>5</td>
<td>(1.5,+)</td>
<td>$RD = 0.4027IIV - 0.3654$</td>
<td>0.6072</td>
</tr>
</tbody>
</table>
The relationship between IIV and RD for different MII groups was plotted in Figure 9. The following tendencies could be observed based on the regression analysis results:

1. There is a linear relationship between the IIV and RD. The R-square values ranged from 0.5432 to 0.7513;
2. Within each MII group, the RD increases with the increases on IIV values. It indicates that a higher IIV value has a negative impact on the nighttime crashes;
3. For the same VVI, the RD values decreased with the increase on MII; and
4. The increase ratio was high for low MII groups while low for higher MII groups.

CONCLUSIONS

The lighting data for 245 miles of state roads in central Florida collected by a mobile lighting measurement system was analyzed. The illuminance intensity data collected with this method at corridor level was testified to be Log-normal distributed. The distribution parameters were calculated with the collected lighting data. For the designated corridors, the mean and variance of the illuminance intensity ranged from 0.017 to 4 fc and 0.0002 to 35 respectively.

To evaluate the lighting system performance with the parameters derived from the collected lighting data, two new criteria (the mean and standard variance of the natural logarithm of the illuminance intensity) that substitute the average illuminance level and uniformity ratio in the design standard were defined. They can be used to evaluate the existing lighting systems at a corridor levels.

The impact of lighting level on crash rate difference was discussed by
analyzing the relationship among MII, IIV and RD. To reflect the impact of MII and IIV on RD independently, the dataset was grouped based on the values of MII and IIV, respectively.

For groups with similar IIV values, the power function was used to model the relationship between MII and RD with R-square values ranging from 0.4 to 0.75. The RD values vary dramatically for low MII level but almost keep at the same level for higher MII period. The regressed functions also indicated that for the same MII value, larger RD values could be achieved for groups with high IIV values.

For groups with similar MII values, a linear regression model was used to predict the relationship between the RD and IIV. The RD values increase with increase on illuminance intensity variance. The increase rate was high for low MII groups while low for high MII groups. The regression model also indicated that for the same IIV value, smaller RD values could be expected for groups with higher MII values.
REFERENCES


7. Road Lighting as an Accident Countermeasure, 1992, Publication CIE 93, International Commission on Illumination, Vienna, Austria.


APPENDIX DISTRIBUTION OF ILLUMINANCE INTENSITY ON EACH CORRIDOR

Figure 10 Distribution of Illuminance Intensity at Roadway 02010000

Note: the horizontal axis in the following graphs represents illuminance intensity level.
Figure 11 Distribution of Illuminance Intensity at Roadway 02030000
Figure 12 Distribution of Illuminance Intensity at Roadway 08010000

Figure 13 Distribution of Illuminance Intensity at Roadway 10005000
Figure 14 Distribution of Illuminance Intensity at Roadway 10020000

Figure 15 Distribution of Illuminance Intensity at Roadway 10030000_1
Figure 16 Distribution of Illuminance Intensity at Roadway 10030000_2

Figure 17 Distribution of Illuminance Intensity at Roadway 10030101
Figure 18 Distribution of Illuminance Intensity at Roadway 10040000

Figure 19 Distribution of Illuminance Intensity at Roadway 10060000
Figure 20 Distribution of Illuminance Intensity at Roadway 10080000

Figure 21 Distribution of Illuminance Intensity at Roadway 10110000
Figure 22 Distribution of Illuminance Intensity at Roadway 10130000

Figure 23 Distribution of Illuminance Intensity at Roadway 10140000
Figure 24 Distribution of Illuminance Intensity at Roadway 10150000

Figure 25 Distribution of Illuminance Intensity at Roadway 10160000
Figure 26 Distribution of Illuminance Intensity at Roadway 10250000

Figure 27 Distribution of Illuminance Intensity at Roadway 10250101
Figure 28 Distribution of Illuminance Intensity at Roadway 10270000

Figure 29 Distribution of Illuminance Intensity at Roadway 10290000
Figure 30 Distribution of Illuminance Intensity at Roadway 10310000

Figure 31 Distribution of Illuminance Intensity at Roadway 10330000
Figure 32 Distribution of Illuminance Intensity at Roadway 14030000

Figure 33 Distribution of Illuminance Intensity at Roadway 15007000
Figure 34 Distribution of Illuminance Intensity at Roadway 15010000

Figure 35 Distribution of Illuminance Intensity at Roadway 15030000
Figure 36 Distribution of Illuminance Intensity at Roadway 15040000

Figure 37 Distribution of Illuminance Intensity at Roadway 15110000
Figure 38 Distribution of Illuminance Intensity at Roadway 15120000

Figure 39 Distribution of Illuminance Intensity at Roadway 15150000