Safety Effects of Street Illuminance on Urban Roadways

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Nighttime Crash Facts in Florida

Fatal Crashes in Florida, 2015

- Daytime 40%
- Nighttime 60%

Only 21-23% of the vehicle miles traveled (VMT) occurred at night.

Pedestrian Fatal Crashes in Florida, 2015

- Daytime 21%
- Nighttime 79%

Source: NHTSA FARS 2015
Background

- Nighttime crashes are overrepresented.
- Many pedestrian and bicycle crashes occur at night.
- Roadway illumination is a vital component of safety.
- A better way to collect lighting level data safely and effectively is necessary.
- Knowledge on how the lighting illumination levels affect nighttime crashes is needed.
- It is beneficial to develop crash modification factors (CMFs) of street illuminance for roadway segments.

Street Lighting Requirements

- A safety countermeasure to reduce nighttime crashes.
  - Provide additional visibility to drivers
  - Significantly improve sight distance for hazard detection
  - Make roadside obstacles more noticeable to drivers

- FDOT Roadway Lighting Requirements

<table>
<thead>
<tr>
<th>Road Classification</th>
<th>Illumination Level</th>
<th>Uniformity Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Initial HFC</td>
<td>Avg/ Min</td>
</tr>
<tr>
<td>Interstates,</td>
<td>1.5</td>
<td>4:1 or less</td>
</tr>
<tr>
<td>Expressways,</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Freeways, and</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Major Arterials</td>
<td></td>
<td></td>
</tr>
<tr>
<td>All other</td>
<td>1.0</td>
<td>4:1 or less</td>
</tr>
<tr>
<td>Roadways</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pedestrian Ways</td>
<td>2.5</td>
<td>4:1 or less</td>
</tr>
<tr>
<td>and Bicycle Lanes</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
DATA COLLECTION CHALLENGES

• Costly ($5,000+/mile)
• Worker safety concerns
• Driver safety concerns
• Manpower
• Accuracy/reliability

DEVELOPMENT OF ADVANCED ILLUMINATION MEASUREMENT SYSTEM (ALMS)
Technical Specifications of ALMS

- Current version: 2.1
- Up to 6 lighting meter inputs
  - Horizontal illumination (2 inputs)
  - Vertical illumination (required by ANSI/ISENA RP-8-00 for pedestrian-vehicle conflicting areas)
- High accuracy
- Resolution: 10 feet
- Speed: ≥ 40 mph
- Special Event logger

Event Logger

Intersection
[1] - Beginning of Intersection
[2] - End of Intersection

Light Poles
[3] - Instances where there’s a light pole

Tree Blockage
[4] - Instances where there’s a light source obstruction

Crosswalks
[5] - Location of a crosswalks (including intersection crosswalks)

Special Light Source
[6] - Any instances of light sources besides light poles (signs, buildings, etc.)

Oncoming Vehicle Light
[7] - Vehicle Lights approaching ahead or behind
ALMS Outputs: Point Data in GIS

Data points are automatically collected for each lane every 10 feet.

ALMS Outputs: Heatmap

Points are aggregated and averaged based on the roadway's characteristics (number of lanes, light source locations, etc.)
Accuracy Validation of ALMS Data

Assessed by Tindale-Oliver & Associates, Inc. Independently

APPLICATION OF ALMS DATA
• Completed data collection for **300+ centerline miles** in southwest Florida
• 2012 - 2017
• This amount is still in expanding.

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**Assessment of Intersection and Roadway Street Lighting Conditions**

- E Fletcher Ave. @ N 15th St.
- Lighting level data showed lighting variance at intersection quadrants.
- Crash data were correlated to prioritize upgrading the quadrant lighting.
Identification of Lighting Issues on a Corridor

- E. Fletcher Ave.
- Lighting level data showed lower levels at the parts of the street where trees were planted.
- Tree trimming was the 1st priority action recommended by TECO in early 2013.
- The tree canopies were trimmed by the County.

Comparison of Corridor Lighting Levels to FDOT Roadway Lighting Requirement

- Can be used to determine corridor lighting level values.
- Can be used to verify “accuracy” of corridor lighting design.
Comparison of Different Street Lighting Technologies

High Pressure Sodium (HPS)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.03</td>
</tr>
<tr>
<td>Max</td>
<td>2.92</td>
</tr>
<tr>
<td>Avg</td>
<td>1.07</td>
</tr>
<tr>
<td>Avg/Min</td>
<td>35.66</td>
</tr>
<tr>
<td>Max/Min</td>
<td>97.33</td>
</tr>
</tbody>
</table>

Light-emitting Diode (LED)

<table>
<thead>
<tr>
<th>Metric</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min</td>
<td>0.03</td>
</tr>
<tr>
<td>Max</td>
<td>4.05</td>
</tr>
<tr>
<td>Avg</td>
<td>0.43</td>
</tr>
<tr>
<td>Avg/Min</td>
<td>13.29</td>
</tr>
<tr>
<td>Max/Min</td>
<td>126.69</td>
</tr>
</tbody>
</table>

Comparison of Different Street Lighting Designs

Wesley Chapel Blvd

Wesley Chapel Blvd
**Determination of Street Lighting Level Depreciation**

Comparison of lighting levels measured in 2007 and with those in 2014:

<table>
<thead>
<tr>
<th>Road Segment</th>
<th>Yearly Lighting Level Depreciation</th>
<th>% Yearly Lighting Level Depreciation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gulf to Bay @ Highland Ave to Lake Drive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hillsborough Ave @ N Armenia Ave to 50th St:</td>
<td>0.045625</td>
<td>3.04%</td>
</tr>
<tr>
<td>@ Armenia Ave N to Nebraska Ave N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Nebraska Ave to 50th St N</td>
<td></td>
<td></td>
</tr>
<tr>
<td>@ Nebraska Ave to N 50th St</td>
<td></td>
<td></td>
</tr>
<tr>
<td>34th St N @ 38th Ave N to 50th Ave N</td>
<td>0.067142857</td>
<td>4.48%</td>
</tr>
<tr>
<td>34th St N @ 13th Ave N to 30th Ave N</td>
<td>0.092857143</td>
<td>6.19%</td>
</tr>
<tr>
<td>Fowler Ave @ 15th St -- NE corner only</td>
<td>0.014285714</td>
<td>0.62%</td>
</tr>
</tbody>
</table>

**Assessment of Lighting Level on Sidewalks**

- Lighting level data showed that existing lighting design addresses roadway AND sidewalk lighting.
- Past street lighting design criteria addresses lighting level on the roadway only (no sidewalk).

**Future guidelines for a site development?**
Assessment of LED Street Lighting Technology

<table>
<thead>
<tr>
<th>LED Street</th>
<th>Start</th>
<th>End</th>
<th>Center Mileage</th>
</tr>
</thead>
<tbody>
<tr>
<td>W Platt Street</td>
<td>S Armenia Ave.</td>
<td>Bayshore Blvd.</td>
<td>1.57</td>
</tr>
<tr>
<td>Dickman Road</td>
<td>Big Bend Rd.</td>
<td>Noonan Branch Rd.</td>
<td>0.51</td>
</tr>
<tr>
<td>SR60</td>
<td>George Pl.</td>
<td>Philip Lee Blvd.</td>
<td>0.52</td>
</tr>
<tr>
<td>E 7th Avenue</td>
<td>Nick Nuccio Parkway</td>
<td>N 40th St.</td>
<td>2.0</td>
</tr>
<tr>
<td>SR 78</td>
<td>-</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>CR 54</td>
<td>I-75 West</td>
<td>750 feet of Progress Parkway</td>
<td>1.2</td>
</tr>
</tbody>
</table>

LED Evaluation: Before-after Study on CR 54

High Pressure Sodium (HPS) Light-emitting Diode (LED)
Past Studies

- Most studies considered the presence of roadway lighting.
- Limited studies assessed safety effects of photometric measures (horizontal illuminance, horizontal luminance, STV) of street lighting.
  - Inconsistent, even counterintuitive conclusions
  - Few studies considered uniformity
  - Outdated lighting and crash data
Research Objectives

• To address the effects of street lighting measures (illuminance mean and uniformity) on nighttime crash occurrence using latest data collected in Florida’s roadway segments
  – nighttime crash frequency
  – night-to-day crash ratio

• To develop crash modification factors (CMFs) of street illuminance for roadway segments
  \[ CMF = \frac{\text{Expected Crash Number after Treatment}}{\text{Expected Crash Number before Treatment}} \]

Site Selection

• A total of 403 roadway segments with street lights were selected.
  – Between two successive signals
  – 500 feet or longer
  – High Pressure Sodium (HPS)
  – No upgrade in past four years

• A 250-ft buffer was subtracted from two ends.
Illuminance Measures

- **Average Illuminance**
  
  \[ MI = \text{Mean}(FC_i) \]
  
  \[ LMI = \ln(MI) \]
  
  \[ MLI = \text{Mean}((\ln(FC_i)) \]

- **Uniformity**
  
  \[ MMR = \frac{\text{Max}(FC_i)}{\text{Min}(FC_i)} = \frac{95\text{th Percentile of } FC_i}{5\text{th Percentile of } FC_i} \]
  
  \[ \text{SDLI} = \sqrt{\text{Var}((\ln(FC_i))} \]

  \( FC_i \) is illuminance (at foot-candle) at measure point \( i \)

<table>
<thead>
<tr>
<th>Variable Description (number of observations: 403)</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Max.</th>
<th>Min.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Crash Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Number of nighttime crashes (four years, 2011–2014)</td>
<td>5.486</td>
<td>9.885</td>
<td>148</td>
<td>0</td>
</tr>
<tr>
<td>Number of daylight crashes (four years, 2011–2014)</td>
<td>16.655</td>
<td>24.844</td>
<td>311</td>
<td>0</td>
</tr>
<tr>
<td><strong>Traffic Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual average daily traffic (AADT)</td>
<td>30,466</td>
<td>16,763</td>
<td>84,750</td>
<td>4,350</td>
</tr>
<tr>
<td>Log (AADT)</td>
<td>10.13</td>
<td>0.687</td>
<td>11.35</td>
<td>8.38</td>
</tr>
<tr>
<td><strong>Geometric Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Length of roadway segment (mi)</td>
<td>0.502</td>
<td>0.595</td>
<td>6.566</td>
<td>0.095</td>
</tr>
<tr>
<td>Access density (number of access points per mi)</td>
<td>11.764</td>
<td>8.968</td>
<td>44.872</td>
<td>0</td>
</tr>
<tr>
<td><strong>Average Illuminance Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean illuminance (MI) at foot-candle (fc)</td>
<td>0.678</td>
<td>0.320</td>
<td>1.432</td>
<td>0.019</td>
</tr>
<tr>
<td>Log (Mean illuminance) (LMI)</td>
<td>-0.612</td>
<td>0.844</td>
<td>0.359</td>
<td>-3.968</td>
</tr>
<tr>
<td>Mean of Logarithm of illuminance (MLI)</td>
<td>-1.053</td>
<td>1.008</td>
<td>0.212</td>
<td>-5.224</td>
</tr>
<tr>
<td><strong>Illuminance Uniformity Variables</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Good uniformity indicator (1 if max/min ≤ 6, 0 otherwise)</td>
<td>0.149</td>
<td>0.356</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Standard deviation of logarithm of illuminance (SDLI)</td>
<td>1.307</td>
<td>0.452</td>
<td>3.760</td>
<td>0.508</td>
</tr>
</tbody>
</table>
Modeling Methods

- Zero-Inflated Negative Binomial (ZINB) Model
  - Expected nighttime crash frequency (N)
  - Expected daytime crash frequency (D)

- Night-to-day crash ratio
  - N/D
  - Eliminate influence of confounding factors

- Night-to-day crash ratio change (Lighting Condition A to B)

\[ P_{A \rightarrow B} = \frac{\frac{N_B}{D_B} - \frac{N_A}{D_A}}{\frac{N_A}{D_A}} \times 100\% = \left( \frac{N_B}{N_A} \times \frac{D_A}{D_B} - 1 \right) \times 100\% \]

Fitted ZINB Model

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coefficient (t-statistic)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Nighttime Model</td>
</tr>
<tr>
<td>Count Equation</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>-5.468 (-6.28)</td>
</tr>
<tr>
<td>Log (AADT)</td>
<td>0.756 (9.31)</td>
</tr>
<tr>
<td>Access density</td>
<td>0.038 (7.09)</td>
</tr>
<tr>
<td>Log (mean illuminance) [LMI]</td>
<td>-0.1068 (-2.09)</td>
</tr>
<tr>
<td>Good uniformity indicator (1 if max/min ≤ 6, 0 otherwise)</td>
<td>-0.283 (-2.54)</td>
</tr>
<tr>
<td>Logarithm of over-dispersion parameter, log(α)</td>
<td>-1.345 (-8.59)</td>
</tr>
<tr>
<td>Inflation Equation</td>
<td></td>
</tr>
<tr>
<td>Constant</td>
<td>0.435 (1.49)</td>
</tr>
<tr>
<td>AADT: multiples of 10,000</td>
<td>-0.490 (-5.02)</td>
</tr>
<tr>
<td>Model Statistics</td>
<td></td>
</tr>
<tr>
<td>Number of observations</td>
<td>403</td>
</tr>
<tr>
<td>Zero observations</td>
<td>138</td>
</tr>
<tr>
<td>Log likelihood</td>
<td>-930.733</td>
</tr>
<tr>
<td>Pseudo R²</td>
<td>0.130</td>
</tr>
<tr>
<td>AIC</td>
<td>1877.466</td>
</tr>
<tr>
<td>BIC</td>
<td>1909.457</td>
</tr>
<tr>
<td>Vuong statistics</td>
<td>5.01</td>
</tr>
</tbody>
</table>
Average Illuminance

• A unit increase in the logarithm of mean illuminance will reduce 0.6 expected nighttime crashes per 4 years.
  – Night time model: -0.1068 (-2.09)
  – Daytime model: -0.0295 (-0.59)

• Impacts of confounding variables cannot be ignored
  – AADT and LMI is positively correlated
    • (Pearson coefficient = 0.224, p-value = 0.000)
  – High illumination associates with high-level geometric design, safety treatments, ...

Illuminance Uniformity

• Good uniformity (max/min < 6) significantly decreases the expected nighttime crash frequency by 1.6 crashes (per 4 years)
  – frequent changes of contrasting high- and low-lit patterns may result in drivers’ weakened vision.

• Significance in Daytime Model (cof. = -0.259, p-value = -2.54)
  – Confounding impacts
  – High uniformity associates with high-level geometric design, safety treatments, ...
Expected Nighttime Crash Frequency

- **Overall**
- **Good Uniformity**
- **Poor Uniformity**

Average Horizontal Illuminance (fc)

- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1
- 1.2
- 1.4
- 1.6

Expected Nighttime Crash Frequency (per 4-years)

- 3.5
- 4
- 4.5
- 5
- 5.5
- 6
- 6.5
- 7

Mean Horizontal Illuminance

- 0
- 0.2
- 0.4
- 0.6
- 0.8
- 1
- 1.2
- 1.4
- 1.6

Expected Night-to-Day Crash Ratio

- **Average Illuminance**

\[ P_{0.1 \text{ fc} \rightarrow x} = \left( \frac{x}{0.1} \right)^{(-0.0733)} - 1 \times 100\% \]

- **Uniformity**

\[ P_{P \rightarrow G} = \{EXP(-0.2825 + 0.2594) - 1\} \times 100\% = -2.3\% \]

\[ CRF = [EXP(-0.283) - 1] \times 100\% = -24.6\% \]
Crash Modification Factors

• Average Horizontal Illuminance

\[ CMF_{NF} = x^{-0.1068} \times 100\% \]  
Based on expected nighttime crash frequency

\[ CMF_{N-D} = x^{-0.0773} \times 100\% \]  
Based on expected N-D ratio

• Uniformity (Good over Poor)

\[ CMF_N = 1 + [EXP(-0.283) - 1] \times 100\% = 75.4\% \]

\[ CMF_{N-D} = 1 + \{EXP(-0.2825 + 0.2594) - 1\} \times 100\% = 97.7\% \]

Summary of Research Findings

• An increase in horizontal illuminance significantly decreases either expected nighttime crash frequency or expected night-to-day crash ratio on roadway segments.

  – The logarithm of average illuminance was superior to average illuminance and average logarithm of illuminance in crash modeling to represent the average street lighting level.

  – Night-to-day crash ratio-based CMF is preferred since night-to-day crash ratio can hedge the influence from the confounding variables

\[ CMF_{N-D} = x^{-0.0773} \times 100\% \]
Summary of Research Findings

• Good illuminance uniformity (max/min < 6) can significantly reduce expected nighttime crash frequency.

CONCLUSIONS

• Agencies can have significant savings of manpower, time, and money on roadway lighting level data collection using ALMS.
• ALMS makes roadway lighting level data collection much safer and make regular roadway lighting level measurements possible.
• ALMS data provide the next level for nighttime crash data analysis.
• The CUTR research team developed crash modification factors of street illuminance for roadway segments.
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