To Illuminate or Not to Illuminate: Roadway Lighting as It Affects Traffic Safety at Intersections

Mark Rea
Lighting Research Center
Rensselaer Polytechnic Institute

Eric Donnell
Dept. of Civil and Environmental Engineering
Pennsylvania State University

John Bullough
Lighting Research Center
Rensselaer Polytechnic Institute

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What is going on?

Cities turn off streetlights to save money

By Dennis Cauchi, USA TODAY

The old-fashioned streetlight is the recession's latest victim. To save money, some cities and towns are turning off lights on many streets. The cost-cutting moves coincide with changing attitudes about streetlights. Or viewed as helpful safety measures, the lights are increasingly seen by some public officials as an environmental blight, creating light pollution and burning excess energy.

State tests dimmer highway lighting

Route 100 project aimed at energy, cost savings

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Roadway lighting and safety

- Why do we light roadways?
  - “To reduce night accidents, attendant human misery, and economic loss” (IES 2000)

- What do we believe?
We believe...

- Roadway lighting improves visibility, which in turn leads to increased safety (fewer crashes): $A + B = C$
Roadway lighting and safety

- **What is the evidence?**
  - Published literature (IES 1989; CIE 1992; Elvik 1995) and many state policies suggest that roadway lighting can be associated with a 30% nighttime crash reduction.

- **What is the problem?**
  - Potential for sampling bias, small samples, lack of statistical control.
  - Inconsistent empirical findings – higher illuminance levels not always associate with lower nighttime crashes.
So, to illuminate or not to illuminate, that is the question
So, to illuminate or not to illuminate, that is the question
How can we know if lighting really matters?

Converging approaches:

- **Statistical approach** from Minnesota Highway Safety Information System (HSIS) statewide database including lighting and crash data
- **Analytical approach** using visibility coverage areas based on Minnesota DOT practices
Statistical Approach

Eric Donnell
Dept. of Civil and Environmental Engineering
Pennsylvania State University
Background

- National- and state-level guidance documents conclusively state that fixed roadway lighting improves safety
  - MnDOT estimates B/C = 21:1
  - Published safety estimates are:
    - 25-52% lower nighttime accident rate
    - 13-49% fewer nighttime accidents
    - 22-40% reduction in night-day accident ratio

- Most research limited to rural, stop-controlled intersections
Motivation

- Safety effects of lighting at rural, signalized and urban locations not well documented
- Relationship between accidents and traffic volume is not linear
- Observed accident frequencies vary randomly ⟰ expected accident frequencies more meaningful
- Past research has not considered “other” intersection features
- Past research generally ignores daytime lighting effects
Highway Safety Manual

- Published in 2010
- Contains accident prediction algorithms:
  - Base crash prediction models
  - Accident modification factors (AMF)
- Lighting AMF for intersections:

\[
AMF_{\text{int}} = 1 - \left[ (1 - 0.36p_{\text{fni}} - 0.72p_{\text{ini}} - 0.83p_{\text{pni}})p_{\text{ni}} \right]
\]

AMF ≈ 0.96 or 4% reduction in total crashes with lighting
Statistical analysis framework

1. Accident, lighting, and roadway inventory data
2. Data structures
3. Analysis taxonomy
4. Daytime and nighttime model specification and estimation
5. Interpret model parameters
Available data and data structures

- **Highway Safety Information System (HSIS):**
  - Minnesota
    - 6,464 intersections
    - 38,437 reported accidents
- **Analysis period:** 1999 to 2002 (inclusive)
- **Accident, traffic volume, lighting presence, geometric design, and traffic control data**
- **No lighting type or lighting design data**
## Data summary

<table>
<thead>
<tr>
<th>Variable</th>
<th>Minimum</th>
<th>Maximum</th>
<th>Mean</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Night accident frequency (per year)</td>
<td>0</td>
<td>28</td>
<td>0.3655</td>
<td>0.9687</td>
</tr>
<tr>
<td>Day accident frequency (per year)</td>
<td>0</td>
<td>55</td>
<td>1.1211</td>
<td>2.4570</td>
</tr>
<tr>
<td>Major road average daily traffic</td>
<td>40</td>
<td>77,430</td>
<td>8,284</td>
<td>9,381</td>
</tr>
<tr>
<td>Percent heavy vehicles on major road</td>
<td>0</td>
<td>61.11</td>
<td>8.8880</td>
<td>5.1092</td>
</tr>
<tr>
<td>Minor road average daily traffic</td>
<td>1</td>
<td>77,430</td>
<td>3,164</td>
<td>5,179</td>
</tr>
<tr>
<td>Area type indicator (1 = urban/suburban; 0 = rural)</td>
<td>0</td>
<td>1</td>
<td>0.4456</td>
<td>0.4970</td>
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<tr>
<td>Traffic control indicator (1 = signal; 0 = stop-control)</td>
<td>0</td>
<td>1</td>
<td>0.1373</td>
<td>0.3442</td>
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<tr>
<td>Lighting indicator (1 = present; 0 = not present)</td>
<td>0</td>
<td>1</td>
<td>0.4212</td>
<td>0.4938</td>
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<tr>
<td>Intersection type indicator (1 = skew; 0 = cross or tee)</td>
<td>0</td>
<td>1</td>
<td>0.1095</td>
<td>0.3123</td>
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<tr>
<td>Speed indicator* (1 = 50 mph or greater; 0 otherwise)</td>
<td>0</td>
<td>1</td>
<td>0.6731</td>
<td>0.4691</td>
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<tr>
<td>No access control indicator * (1 = no access; 0 = partial access control)</td>
<td>0</td>
<td>1</td>
<td>0.9426</td>
<td>0.2326</td>
</tr>
<tr>
<td>Depressed median indicator* (1 = depressed median; 0 = barrier or no median)</td>
<td>0</td>
<td>1</td>
<td>0.1162</td>
<td>0.3204</td>
</tr>
<tr>
<td>Paved left-shoulder indicator* (1 = paved shoulder; 0 = unpaved or no shoulder)</td>
<td>0</td>
<td>1</td>
<td>0.4577</td>
<td>0.4982</td>
</tr>
<tr>
<td>Paved right-shoulder indicator* (1 = paved shoulder; 0 = unpaved or no shoulder)</td>
<td>0</td>
<td>1</td>
<td>0.5096</td>
<td>0.4999</td>
</tr>
</tbody>
</table>

*indicates that data were used for the major intersecting roadway only
Analysis taxonomy

All Intersections

Urban
- Signalized
- Unsignalized

Rural
- Signalized
- Unsignalized
Evaluative aspects

- Three safety performance measures:
  - Expected number of daytime accidents
  - Expected number of nighttime accidents
  - Percent change in night-to-day accident ratio

- Considered observational before-after study and cross-sectional study
  - Before-after study not possible due to small number of treatment sites during analysis period
  - In cross-sectional study, no treatment applied (with- without comparison)
Statistical modeling approach

- Negative binomial regression:

\[ \ln \lambda_i = \beta X_i + \varepsilon_i \]

- Percent change in night-to-day ratio:

\[ \frac{\left( \frac{N}{D} \right)_w - \left( \frac{N}{D} \right)_{wo}}{\left( \frac{N}{D} \right)_{wo}} \]

Use estimates from lighting parameter in models
### Minnesota model estimation results

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daytime Model</th>
<th>Nighttime Model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameter Estimate</td>
<td>Standard Error</td>
</tr>
<tr>
<td>Constant</td>
<td>-6.5373</td>
<td>0.151</td>
</tr>
<tr>
<td>Log major road average daily traffic</td>
<td>0.6011</td>
<td>0.015</td>
</tr>
<tr>
<td>Percent heavy vehicles on major road</td>
<td>-0.0092</td>
<td>0.003</td>
</tr>
<tr>
<td>Log minor road average daily traffic</td>
<td>0.1603</td>
<td>0.007</td>
</tr>
<tr>
<td>Area type indicator (1 = urban/suburban; 0 = rural)</td>
<td>-0.0992</td>
<td>0.029</td>
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<tr>
<td>Traffic control indicator (1 = signal; 0 = stop-control)</td>
<td>0.6445</td>
<td>0.031</td>
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<tr>
<td>Lighting indicator (1 = present; 0 = not present)</td>
<td>0.0477</td>
<td>0.031</td>
</tr>
<tr>
<td>Intersection type indicator (1 = skew; 0 = cross or tee)</td>
<td>0.4862</td>
<td>0.031</td>
</tr>
<tr>
<td>Speed indicator* (1 = 50 mph or greater; 0 otherwise)</td>
<td>-0.1601</td>
<td>0.022</td>
</tr>
<tr>
<td>No access control indicator * (1 = no access; 0 = partial access control)</td>
<td>-0.0416</td>
<td>0.038</td>
</tr>
<tr>
<td>Depressed median indicator* (1 = depressed median; 0 = barrier or no median)</td>
<td>0.0851</td>
<td>0.034</td>
</tr>
<tr>
<td>Paved left-shoulder indicator* (1 = paved shoulder; 0 = unpaved or no shoulder)</td>
<td>-0.1163</td>
<td>0.042</td>
</tr>
<tr>
<td>Paved right-shoulder indicator* (1 = paved shoulder; 0 = unpaved or no shoulder)</td>
<td>0.0798</td>
<td>0.041</td>
</tr>
<tr>
<td>Dispersion parameter ($\alpha$)</td>
<td>0.9487</td>
<td>0.024</td>
</tr>
</tbody>
</table>

Number of observations = 22,058
LL (constant only) = -28,954.27
LL (full model) = -27,084.31
Pseudo R² = 0.1355

Number of observations = 22,058
LL (constant only) = -17,842.15
LL (full model) = -15,165.85
Pseudo R² = 0.1259
Elasticities (continuous variables)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daytime Elasticity</th>
<th>Nighttime Elasticity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Log major road average daily traffic</td>
<td>0.601</td>
<td>0.574</td>
</tr>
<tr>
<td>Log minor road average daily traffic</td>
<td>0.160</td>
<td>0.126</td>
</tr>
<tr>
<td>Percent heavy vehicles on major road</td>
<td>-0.082</td>
<td>-0.149</td>
</tr>
</tbody>
</table>
## Elasticities (categorical variables)

<table>
<thead>
<tr>
<th>Variable</th>
<th>Daytime</th>
<th>Nighttime</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area type indicator</td>
<td>-10.4</td>
<td>-52.4</td>
</tr>
<tr>
<td>(1 = urban/suburban; 0 = rural)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Traffic control indicator</td>
<td>47.5</td>
<td>50.9</td>
</tr>
<tr>
<td>(1 = signal; 0 = stop-control)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lighting indicator</td>
<td>4.7</td>
<td>-8.2</td>
</tr>
<tr>
<td>(1 = present; 0 = not present)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intersection type indicator</td>
<td>38.5</td>
<td>38.4</td>
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<tr>
<td>(1 = skew; 0 = cross or tee)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speed indicator*</td>
<td>-17.4</td>
<td>-12.0</td>
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<tr>
<td>(1 = 50 mph or greater; 0 otherwise)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>No access control indicator*</td>
<td>-4.2</td>
<td>-1.5</td>
</tr>
<tr>
<td>(1 = no access; 0 = partial access control)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depressed median indicator*</td>
<td>8.2</td>
<td>15.7</td>
</tr>
<tr>
<td>(1 = depressed median; 0 = barrier or no median)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paved left-shoulder indicator*</td>
<td>-12.3</td>
<td>-33.7</td>
</tr>
<tr>
<td>(1 = paved shoulder; 0 = unpaved or no shoulder)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Paved right-shoulder indicator*</td>
<td>7.7</td>
<td>19.4</td>
</tr>
<tr>
<td>(1 = paved shoulder; 0 = unpaved or no shoulder)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
## Percent difference in night-to-day ratio (MN)

<table>
<thead>
<tr>
<th>Intersection Type</th>
<th>Model</th>
<th>Descriptive Statistics</th>
<th>Sample Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>-11.9%</td>
<td>-28.0%</td>
<td>22,058</td>
</tr>
<tr>
<td>Urban Unsignalized</td>
<td>-13.3%</td>
<td>-18.9%</td>
<td>7,730</td>
</tr>
<tr>
<td>Urban Signalized</td>
<td>-6.5%</td>
<td>13.5%</td>
<td>2,875</td>
</tr>
<tr>
<td>Rural Unsignalized</td>
<td>-1.6%</td>
<td>-7.6%</td>
<td>11,101</td>
</tr>
<tr>
<td>Rural Signalized</td>
<td>0.3%</td>
<td>-8.7%</td>
<td>352</td>
</tr>
</tbody>
</table>
Statistical approach conclusions

- Lighting has safety benefit at intersections:
  - 12% lower night-to-day accident ratio in MN
  - Results consistent in NB cross-sectional models, case-control models, and propensity scores-potential outcomes framework
- Model estimates similar to lighting AMF in Highway Safety Manual
- Magnitude of lighting effect lower than past published research (CIE, 1992; Elvik, 1995)
Analytical Approach

John Bullough
Lighting Research Center
Rensselaer Polytechnic Institute
How are Minnesota’s intersections illuminated?

- MnDOT’s Roadway Lighting Design Manual is regularly maintained
- Practices closely follow Illuminating Engineering Society (IES) and American Association of State Highway and Transportation Officials (AASHTO) recommendations
- Photolog spot checks confirm that they “practice what they preach”

<table>
<thead>
<tr>
<th>Roadway Intersection Type</th>
<th>Roadway Illuminance</th>
<th>Intersection Illuminance</th>
<th>Ambient Illuminance</th>
<th>Speed Limit</th>
<th>Extended/Localized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban signalized</td>
<td>18 lx</td>
<td>30 lx</td>
<td>2 lx</td>
<td>30 mph</td>
<td>Extended</td>
</tr>
<tr>
<td>Suburban unsignalized</td>
<td>9 lx</td>
<td>15 lx</td>
<td>0.2 lx</td>
<td>30 mph</td>
<td>Extended</td>
</tr>
<tr>
<td>Rural signalized</td>
<td>6 lx</td>
<td>10 lx</td>
<td>0.2 lx</td>
<td>55 mph</td>
<td>Localized</td>
</tr>
<tr>
<td>Rural unsignalized</td>
<td>6 lx</td>
<td>10 lx</td>
<td>0.02 lx</td>
<td>55 mph</td>
<td>Localized</td>
</tr>
</tbody>
</table>
Visibility analysis approach

- How much (if at all) does lighting, as practiced along roadway intersections in Minnesota, improve visual performance
  - Including the impacts of vehicle headlights (on visibility and glare)
- For:
  - Rural, unsignalized intersections
  - Rural, signalized intersections
  - Urban/suburban, unsignalized intersections
  - Urban/suburban, signalized intersections
- Using:
  - Photometrically accurate, field-verified lighting calculation/simulation software and a validated model of visual performance
Common intersection crash types

- Misjudgment of location/velocity of adjacent vehicles is a common cause of crashes at intersections (after red light running) (Chovan et al. 1994)

Adapted from connectedvehicle.challenge.gov
Potential role of lighting in safety

Which car would you rather be facing?
Visibility coverage area

- Characterizes drivers’ ability to see potential hazards (other vehicles) and surrounding terrain for different driving speeds.
- Includes headlamps, ambient light (in urban/suburban and rural locations), extended (continuous) and localized ("point") lighting, driver age (30, 45 and 60 year olds).

Relevant locations for high speeds (≥40 mph)

Relevant locations for low speeds (<40 mph)

(40 mph = 65 km/h)

Rea et al. 2010
Relative visual performance (RVP) model

- Speed-accuracy is a function of object brightness, contrast, size, and observer age
- Once high visual performance is achieved, further increases in light level do not improve speed-accuracy

Rea and Ouellette 1991
Validation of RVP model under nighttime driving conditions

Pedestrian crosswalk lighting

Intelligent headlights

Bullough et al. 2012

Bullough and Skinner 2012
Target characteristics

- A target with the characteristics specified by the IES (2000) “small target visibility” procedure was used.
- Provides sensitivity for visual performance analysis.

Rea et al. 2010
RVP score
Analytical approach results

<table>
<thead>
<tr>
<th>Roadway Intersection Type</th>
<th>Roadway Illuminance</th>
<th>Intersection Illuminance</th>
<th>Ambient Illuminance</th>
<th>Speed Limit</th>
<th>ΔRVP Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Urban signalized</td>
<td>18 lux</td>
<td>30 lux</td>
<td>2 lux</td>
<td>30 mph</td>
<td>+0.73</td>
</tr>
<tr>
<td>Suburban unsignalized</td>
<td>9 lux</td>
<td>15 lux</td>
<td>0.2 lux</td>
<td>30 mph</td>
<td>+1.86</td>
</tr>
<tr>
<td>Rural signalized</td>
<td>6 lux</td>
<td>10 lux</td>
<td>0.2 lux</td>
<td>55 mph</td>
<td>+0.27</td>
</tr>
<tr>
<td>Rural unsignalized</td>
<td>6 lux</td>
<td>10 lux</td>
<td>0.02 lux</td>
<td>55 mph</td>
<td>+0.21</td>
</tr>
</tbody>
</table>

Visibility ≠ Light Level!

MnDOT 2006; Rea et al. 2010
A provisional transfer function for visibility and nighttime crash safety

\[ y = 0.072x \]

\[ R^2 = 0.93 \]
Applying the provisional transfer function

Roadway lighting, as practiced by MnDOT (based on IES recommendations), would be expected to reduce nighttime crashes by 1.5% at rural unsignalized intersections, and by 5.3% at urban signalized intersections.
Extended lighting

- To the extent visual performance and safety are correlated, it can be possible to optimize lighting beyond existing practices to improve nighttime safety.
- For example: most rural intersection lighting is localized or “point” lighting.
  - Expected to reduce nighttime crashes by 1.5%.
  - An array of five streetlights illuminating the major intersecting roadway and to a higher light level might reduce nighttime crashes by 11% - a sevenfold increase in benefit with an approximately fivefold increase in cost.
Analytical approach conclusions

- The relative visual performance (RVP) model is a robust predictor of speed and accuracy of seeing under nighttime driving conditions.
- Increases in visual performance from roadway intersection lighting are correlated with improvements in nighttime driving safety.
- Increases in visual performance from roadway intersection lighting are not directly correlated with higher horizontal illuminances on the roadway.
Benefit/Cost

Mark Rea
Lighting Research Center
Rensselaer Polytechnic Institute
Economic costs of roadway intersection lighting

- **Installation cost:** Assumes dedicated poles with underground wiring (R.S. Means 2008)
  - Urban signalized: $13,500 (annualized over 20 yr: $1,080)
  - Rural unsignalized: $4,600 (annualized over 20 yr: $370)

- **Operation and maintenance cost:**
  - Urban signalized: $710 (annual)
  - Rural unsignalized: $230 (annual)

- **Overall annual(ized) cost:**
  - Urban signalized: $1,790 (annual)
  - Rural unsignalized: $600 (annual)

- **Cost is unrelated to traffic volume**
Economic benefits of avoided crashes

- U.S. DOT (2008) estimates for different crash severities:
  - Fatality: $5,800,000
  - Incapacitating injury: $401,538
  - Evident injury: $80,308
  - Possible injury: $42,385
  - Property damage only: $4,462

- Fatal and injury crashes are more prevalent at rural locations (higher speeds), so average weighted crash costs are:
  - Urban signalized: $122,056
  - Rural unsignalized: $232,142
Applying the transfer function

Roadway lighting, as practiced by MNDOT (based on IES recommendations), would be expected to reduce nighttime crashes by 1.5% at rural unsignalized intersections, and by 5.3% at urban signalized intersections.

\[
\Delta N/D (\%) = 0.72 \Delta RVP
\]

\[
R^2 = 0.93
\]
Reduction in nighttime crashes associated with roadway intersection lighting

<table>
<thead>
<tr>
<th>Major Road AADT (annual average daily traffic)</th>
<th>Annual Expected Number of Crashes at Urban Signalized Intersections</th>
<th>Annual Expected Number of Crashes at Rural Unsignalized Intersections</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>0.043</td>
<td>0.032</td>
</tr>
<tr>
<td>200</td>
<td>0.065</td>
<td>0.048</td>
</tr>
<tr>
<td>500</td>
<td>0.109</td>
<td>0.082</td>
</tr>
<tr>
<td>1000</td>
<td>0.162</td>
<td>0.121</td>
</tr>
<tr>
<td>2000</td>
<td>0.242</td>
<td>0.181</td>
</tr>
<tr>
<td>5000</td>
<td>0.409</td>
<td>0.306</td>
</tr>
<tr>
<td>10,000</td>
<td>0.609</td>
<td>0.455</td>
</tr>
<tr>
<td>20,000</td>
<td>0.906</td>
<td>0.677</td>
</tr>
<tr>
<td>50,000</td>
<td>1.533</td>
<td>1.146</td>
</tr>
</tbody>
</table>

5.3% of each value × $122,056 = $232,142

1.5% of each value × $232,142
Benefit/cost ratios

Urban signalized intersections

Rural unsignalized intersections
Rural example: Extended lighting

- Changing from localized lighting at rural intersections to extended lighting with a higher illuminance
  - Using an array of five luminaires along the major intersecting roadway
- The alternative lighting would be expected to improve the crash reduction factor from **1.5%** (0.21 ΔRVP units) to **11.0%** (1.53 ΔRVP units)

AADT = 3200 vehicles/day (mean in MN)
Rural example: Extended lighting

Simple payback for installation cost:
< 6 months
Rural example: Adaptive lighting

- Nighttime traffic volume is not uniform throughout the night

50% of crashes are expected during the busiest four hours of the 12-hour night

AADT = 3200 vehicles/day (mean in MN)

Ivan et al. 2002

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Rural example: Adaptive lighting

- Tripling the light level during these hours at a rural unsignalized intersection from 10 to 30 lux would improve the crash reduction factor from 1.5% (0.21 ΔRVP units) to 5.6% (0.78 ΔRVP units).
  - Turning lights off during the remaining 8 hours of the night would result in nominally equal operating costs.
  - Overall crash reduction would be 2.8% (50% x 5.6%), compared to 1.5% for the lower light level throughout entire night.

- Assuming an initial cost of $250 for such a control system, simple payback would occur within four months.

\[
\text{AADT} = 3200 \text{ vehicles/day} \text{ (mean in MN)}
\]
Rural example: Decommissioning

- Switch off lighting, eliminate energy and maintenance costs
  - 1.5% ΔN/D @ 10 lux

Breakeven traffic volume is so much lower because cannot recover pole installation costs
Summary

- Roadway lighting can improve safety
  - Not necessarily as much as previously assumed
- Safety can be increased by increasing visibility
  - Predictions possible, not just post hoc inferences
- Value (benefits/costs) can be now calculated to compare lighting of different types and with other possible safety interventions
Thank you!

Mark Rea
Lighting Research Center
Rensselaer Polytechnic Institute

Eric Donnell
Dept. of Civil and Environmental Engineering
Pennsylvania State University

John Bullough
Lighting Research Center
Rensselaer Polytechnic Institute

References: www.lrc.rpi.edu/lighting-safety