New Directions in Roadway Lighting

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Motivation

• Agencies are looking for a reduction in total cost of ownership
  – Reduction in:
    • Purchase Costs
    • Inventory Costs
    • Maintenance Costs
    • Energy Costs

• This has led to significant changes in the approach to many lighting projects
  – 3P
  – ESCO
  – One for One replacements with Controls
Special Roadway/Outdoor Considerations

- Driver Safety
  - In the US, at least 35,000 people die in vehicular crashes every year
- Mesopic Issues
- Sky Glow Issues
- Melatonin Issues
- Flora and Fauna Issues
Approach

• Use light only where and when it is needed
  – This minimizes the negative impact of the lighting.

• So the Issue:

• How Much Light is needed on a Roadway?
FHWA Strategic Initiative for Reduced Lighting on Roadways

• We linked the lighting level to crash rate for a variety of roadway designs and conditions
  – Developed a statistically accurate link between lighting design and crash safety

• Established Criteria for when to dim lighting
  – Not on and off- dimming
Adaptive Lighting Project Data Collection

- Capturing Light and Crash Data from 7 states
  - HSIS Four States: WA, MN, CA, NC
  - Additional States: VA, DE, VT
In-Situ Lighting Data Collection

• On-site visits to each one for the test sites identified.
  – The lighting design and roadway geometry was verified.
  – The travel lanes closest to the luminance and farthest away from the luminaire were driven for the entire test section.
  – During that driving time, an on-vehicle data collection system will capture all of the lighting parameters required.
Equipment

External

- Novatel GPS device mounted at the center of the vehicle
- Illuminance Meter Grid
  - Four weatherproof heads mounted horizontally on the roof of the vehicle in the center of the wheel path

Internal

- Illuminance Meter
  - One mounted vertically inside the windshield
- Luminance Camera
  - VTTI-developed luminance camera to monitor the entire scene
  - Luminance is derived from a calibration procedure performed on each camera
- Color Camera
  - 1280x960 RGB FireWire camera
- J1850 box
  - Returns vehicle information from internal vehicle CAN network
- Spectroradiometer
  - Ocean Optics HR4000
  - Measures spectral information through a fiber optic link to a cosine or sphere collector on vehicle roof
- Buttons
  - Small push buttons mounted in vehicle to capture human response events
- Eye Tracker
  - Arrington Research Binocular Eye Tracking System
System Layout
Output
Analysis

• Compared the lighting level to crash rate ratios for 83,000 crashes and 2000 miles of roadway lighting
Results

![Graph showing comparison between Non-Lighted and Lighted conditions in terms of Night-to-Day Crash Rate Ratio against Horizontal Illuminance (Lux). The graph indicates a decrease in crash rate with increasing illuminance for both conditions, with the Non-Lighted condition starting higher than the Lighted condition. Error bars are also shown to indicate variability.]
Lighting Quality

![Graph showing the relationship between lighting quality and crash rate ratio. The x-axis represents the uniformity metric, and the y-axis shows the night-to-day crash rate ratio. The graph indicates a downward trend as the uniformity metric increases.](image)
Results by Road Type

![Graph showing night-to-day crash rate ratio by illuminance for different road types. The x-axis represents illuminance (Lux) ranging from 0 to 30, and the y-axis represents the night-to-day crash rate ratio ranging from 0 to 2.5. The graph includes lines for Urban Interstate, Urban Principal Arterial, Urban Other Principal Arterial, and Urban Minor Arterial, each with error bars indicating variability.](image-url)
Comparison with the IES Requirements

![Bar chart showing comparison between different road classifications and their horizontal illuminance requirements.

- **Urban Interstate**: Minimum requirement (blue) is around 5 lux, low IES requirement (orange) is around 8 lux, and high IES requirement (gray) is around 16 lux.
- **Urban Principal Arterial**: Minimum requirement is around 7 lux, low IES requirement is around 9 lux, and high IES requirement is around 16 lux.
- **Other Principal Arterial**: Minimum requirement is around 10 lux, low IES requirement is around 11 lux, and high IES requirement is around 16 lux.
- **Minor Arterial**: Minimum requirement is around 12 lux, low IES requirement is around 13 lux, and high IES requirement is around 17 lux.

Legend:
- Blue: Minimum Illuminance Requirement (lux)
- Orange: Low IES Requirement
- Gray: High IES Requirement

Transportation Institute
Visibility Tests

- Objective assessment of small target visibility
- Response metric (object detection distance)
- Illuminance and luminance metrics (meters mounted on the car)
San Jose Streetlight Demonstration

- Full power night 1 (wet pavement)
- 50% power night 2 (dry pavement)
- 6 types of lights: HPS, LPS, Induction & 3 LED
San Jose – Detection distance vs. watts per linear foot **HIGH (100%)** setting
San Jose – Detection distance vs. watts per linear foot LOW (50%) setting
Guidelines for Adaptive Lighting

• With the advent of new control and ballast technology we have the ability to adapt a roadway lighting system to the needs of the environment.
  – Traffic Volume
  – Weather
  – Lighting Condition
  – Pedestrian Usage

• Adaptive Lighting basically represents the lowering or raising of the light level based on the needs of the roadway and the drivers
  – This requires dimming capabilities
Adaptive Process

• Lighting level is selected based on the roadway conditions
Adaptive Approaches

• 2 approaches are currently being utilized:
  • IES  
  • FHWA/VTTI

• Research has shown that dividing the road by usage type impacts the lighting requirements
  • Eye Tracking shows different drivers eye behavior
The IESNA does not speak for or against Adaptive Lighting

<table>
<thead>
<tr>
<th>Selected Street Classification</th>
<th>Selected Pedestrian Classification</th>
<th>Average Luminance (cd/m²)*</th>
<th>Evening</th>
<th>Late Night</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major</td>
<td>High</td>
<td>1.2</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collector</td>
<td>High</td>
<td>0.8</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.4</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Minor</td>
<td>High</td>
<td>0.6</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>0.3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
FHWA/VTTI Proposal

• 3 Categories of Lighting Criteria
  – Roadway – High Speed with no Pedestrian Interaction
  – Street – Major Roadways with Potential Pedestrians, Speed > 25mph, Moderate to high Traffic Volumes
  – Pedestrians/Residential – Speeds < 25 mph – Lighting is primarily for pedestrians

• Adaptive Lighting
  – When the conditions change to allow for a different class – It is determined by the selection criteria and the weighting factors.
Process

• Calculate Weighting factors from selection criteria.
• Subtract Weighting from base number to determine class
• Obtain Design Values for the Class
Setting the Class

Lighting Class = Base Value - \sum \text{Weighting Values}
# Roadway Lighting

Base value for class: 5

## Table 1. Roadway design level selection criteria.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Options</th>
<th>Criteria</th>
<th>Weighting V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Very High</td>
<td>&gt; 60 mi/h (100 km/h)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>High</td>
<td>45–60 mi/h (75 –100 km/h)</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>&lt; 45 mi/h (75 km/h)</td>
<td>0</td>
</tr>
<tr>
<td>Traffic Volume</td>
<td>High</td>
<td>&gt; 30,000 ADT*</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>10,000 - 30,000 ADT</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>&lt; 10,000 ADT</td>
<td>-1</td>
</tr>
<tr>
<td>Median</td>
<td>No</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Yes</td>
<td>Must be glare blocking</td>
<td>0</td>
</tr>
<tr>
<td>Intersection/Interchange Density</td>
<td>High</td>
<td>&lt; 1.5 miles between intersections (2.5 km)</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>1.5–4 miles (2.5 km – 6.5 km) between intersections</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>&gt; 4 miles (6.5 km) between intersections</td>
<td>-1</td>
</tr>
<tr>
<td>Ambient Luminance</td>
<td>High</td>
<td>LZ3 and LZ4</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Moderate</td>
<td>LZ2</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Low</td>
<td>LZ1</td>
<td>-1</td>
</tr>
<tr>
<td>Guidance</td>
<td>Good</td>
<td>&gt; 100 mcd/m² lx**</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Poor</td>
<td>&lt; 100 mcd/m² lx</td>
<td>0.5</td>
</tr>
</tbody>
</table>

*ADT = Average Daily Traffic  
**mcd/m² lx = millicandela/meter squared lux
# H Class

Table 1. H-Class lighting design levels.

<table>
<thead>
<tr>
<th>Class</th>
<th>Average Luminance (cd/m²)</th>
<th>Max Uniformity Ratio (avg/min)</th>
<th>Max Uniformity Ratio (max/min)</th>
<th>Veiling Luminance Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>H1</td>
<td>1</td>
<td>3</td>
<td>5</td>
<td>0.3</td>
</tr>
<tr>
<td>H2</td>
<td>0.8</td>
<td>3.5</td>
<td>6</td>
<td>0.3</td>
</tr>
<tr>
<td>H3</td>
<td>0.6</td>
<td>3.5</td>
<td>6</td>
<td>0.3</td>
</tr>
<tr>
<td>H4</td>
<td>0.4</td>
<td>3.5</td>
<td>6</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Wet Dry

- It is not clear – More factors need to be considered:
  - Wet and Dry Conditions
  - Impact of Glare
    - Used an Asymmetric Luminaire Distribution
  - Impact of Uniformity
    - Considered typical non-uniformity / Asymmetric
Micro Scale Lighting Requirements

• Our approach to lighting design is relatively broad scale.

• What about the microscale design issues?
  – Is lighting required on a tangent section or just curves?
  – New approaches to Human Factors research might provide a clue.
Evolution of Naturalistic Research into Distraction

- Naturalistic data collection techniques were developed by VTTI to capture naturally occurring driver behavior, to the extent practical
  - Long data collection periods (up to 3 years)
  - Minimal intervention during data collection
- In situ naturalistic driving data collection methods allow an unobtrusive, real-world observation of driver behavior and performance
- Naturalistic data collection can be used to estimate prevalence and risk regarding drivers’ secondary task distractions and crash rates
- VTTI is the pioneer, housing more than 40 million miles of continuous naturalistic driving data
- We overlapped the lighting measurements with lighting efforts
Three Approaches to Consider

- Time Series Data
- Event Data
- Crash Data
SHRP 2 Time Series Data Analysis

• Statistical analyses
  – Multiple regression, multiple comparison procedures (MCPs)

• Five analysis segments, two types of ramps, and two types of traffic

• Multiple safety counter measures:
  – Speed and speed variance, longitudinal acceleration, lateral acceleration, lane offset, head position and rotation, and time to collision

: 200-foot analysis area.
# Data Used

<table>
<thead>
<tr>
<th>Data Type</th>
<th>Sample Size</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp data</td>
<td>Ramps mostly on two 10-mile freeway segments</td>
<td>Ramp type, main lane alignment, number of main lanes, number of ramp lanes, auxiliary lane length</td>
</tr>
<tr>
<td>Lighting data</td>
<td>Right lane and overall lighting measurements</td>
<td>Lighting data were based on field lighting measurements by VTTI</td>
</tr>
<tr>
<td>Time series data</td>
<td>1.8 million data points, 58,467 records, 1,270 trips, 313 drivers</td>
<td>Time series data were matched to lighting data using GIS. The large amount of data required significant computing resources and time</td>
</tr>
<tr>
<td>Events data</td>
<td>31 suitable events at interchange areas</td>
<td>Selected night-time events at interchange areas in Washington</td>
</tr>
<tr>
<td>RID crash data</td>
<td>46 ramp segments for analysis, 69 night crashes</td>
<td>2011-13 crash data used for analysis. Only a limited number on analysis segments</td>
</tr>
</tbody>
</table>
Lighting Metrics

- Horizontal illuminance
- Lighting uniformity
Time Series Analysis Results – Entrance Ramp

Entrance Ramp: Driver Behavior - Increase in Illuminance

<table>
<thead>
<tr>
<th>Analysis Segment</th>
<th>Traffic Type</th>
<th>Right-Lane Illuminance</th>
<th>Overall Illuminance</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>EN1</td>
<td>EN2</td>
</tr>
<tr>
<td>Speed</td>
<td>Ramp</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>Through</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Longitudinal</td>
<td>Ramp</td>
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<td>Longitudinal</td>
<td>Through</td>
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<td>Longitudinal</td>
<td>Ramp</td>
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<tr>
<td>Longitudinal</td>
<td>Through</td>
<td>NS</td>
<td>NS</td>
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<tr>
<td>Lateral Acceleration</td>
<td>Ramp</td>
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<tr>
<td>Lateral Acceleration</td>
<td>Through</td>
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<td>NS</td>
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<tr>
<td>Lateral Acceleration</td>
<td>Ramp</td>
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<tr>
<td>Lateral Acceleration</td>
<td>Through</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>Lane Offset</td>
<td>Ramp</td>
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<tr>
<td>Lane Offset</td>
<td>Through</td>
<td>NS</td>
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</tr>
</tbody>
</table>
### Time Series Analysis Results – Entrance Ramp

#### Entrance Ramp: Driver Behavior - Increase in Uniformity

<table>
<thead>
<tr>
<th>Analysis Segment</th>
<th>Traffic Type</th>
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<tr>
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<td>Ramp</td>
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<td>NS</td>
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<td>Through</td>
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<td>NS</td>
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</table>
Future Issues

• Impact on Flora and Fauna
The Future

• Long Range
  – More Automation
  – Driver-less vehicles
  – Vehicles on demand