Towards LED Roadway Lighting: State Transportation Agency Guidelines

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ABSTRACT
Roadway and street lighting across the nation consumes a large amount of energy and is responsible for significant tonnage of carbon dioxide (CO₂). As the nation continues to conserve energy and reduce CO₂ emission, and as state and local transportation agencies strive to save operational costs, light emitting diode (LED) roadway lighting technology becomes increasingly appealing. Currently, many state transportation agencies (STAs) lag in statewide implementation of LED roadway lighting, partly due to a lack of technology understanding and concerns for relevant safety and liability issues. The Virginia Department of Transportation recently launched a significant effort to assess the LED roadway lighting technology and LED performance over time. The effort involved laboratory and field tests of five different designs of LED roadway luminaires over a period of two years. This paper presents selected findings of the project as they benefit STAs during the LED implementation process. The paper includes a detailed performance comparison between the LED and the traditional high pressure sodium (HPS) lighting technologies, guidelines for developing LED roadway luminaire specifications at STAs, and recommendations to facilitate the LED implementation process at states. Overall, the study found that the LED luminaires outperformed HPS systems in light quality, but different LED luminaire designs exhibited very different performance characteristics. The light output of the LED systems decreased during the first two years, but not significantly when considering performance variation and ambient factors. The study also found that LED fixtures should have proper ingress protection and needed to be properly installed.
INTRODUCTION AND LITERATURE REVIEW
Roadway and street lighting across the nation consumes a large amount of energy and is responsible for significant tonnage of carbon dioxide (CO\textsubscript{2}). The Department of Energy (DOE) estimated that the 26.5 million streetlights in the country consumed as much electricity each year as did 1.9 million households, and generated greenhouse gas equivalent to that produced by 2.6 million cars (I). As the nation continues to make efforts in conserving energy and reducing CO\textsubscript{2} emission, and as state and local transportation agencies strive to save operational costs, more efficient roadway lighting technologies are becoming increasingly appealing. Among the various emerging technologies, light emitting diodes (LEDs) are currently gaining popularity for general illumination applications. LEDs typically have a much longer service life and provide higher luminaire efficacy than traditional sources. Their light output is also a much broader spectrum than other sources, meaning that the light appears to be white and provides proper color appearance. This feature can result in an improved visual performance for the same design light level of traditional lighting technologies.

While providing the benefits of energy efficiency and superior light quality, however, LEDs have changed the lighting industry. Traditionally, the lighting industry has been dominated by a small number of companies who had extensive experience in providing products that would be able to withstand the sometimes harsh roadway environment. With the emerging of LED technology, small, typically electronics companies have started the development of roadway lighting systems. Luminaires developed by such manufacturers may have issues with system durability and the ease for roadway installation. In addition, the luminaires must match the requirements of roadway lighting applications to provide a proper light distribution while reducing glare and uplight. With the advent of these less experienced companies and even the production of the new technology by traditional lighting companies, it is important that careful evaluations of LED luminaires be made before a full scale implementation can be undertaken.

To develop a comprehensive understanding of this fast evolving technology, stakeholders have launched various studies across the nation. The U.S. Department of Energy (DOE), for example, is performing a large-scale field assessment of SSL performance for general illumination in exterior and interior applications, known as the SSL Technology Demonstration GATEWAY program(2, 3). Some state DOTs and municipalities also conducted similar studies to understand LED technology (4, 5, 6, 7). Past experience with LED technology in roadway lighting has suggest that the light efficacy of LED roadway lighting systems currently is comparable to that of HPS in roadway lighting applications, but is improving rapidly and is expected to significantly exceed that of other traditional technologies in the near future. Most studies concluded that the light quality of LED systems, such as light color, distribution, perception, and ground illuminance, was superior to that of traditional lighting technologies (3). Note that many previous LED lighting studies were based on software-simulated data and/or relatively short-term lighting data measurements. As such, few studies have resulted in a thorough understanding of LED lumen maintenance over time based on field measurements.

Currently, many state transportation agencies (STAs) lag in statewide implementation of LED roadway lighting, partly due to a lack of technology understanding and concerns for relevant safety and liability issues. Recognizing the critical needs for energy conservation and better lighting, the Virginia Department of Transportation (VDOT) launched a significant effort to
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assess the LED roadway lighting technology and LED performance over time from a STA implementation perspective (8). As part of this project, the research team conducted laboratory and field tests of five different designs of LED roadway luminaires over a period of two years and compared their key performance metrics with the traditional high pressure sodium (HPS) lighting technology widely used on the nation’s roadways. In addition, the research team conducted a detailed cost-benefit analysis to quantify the potential benefits of LED roadway luminaires over their service life. Based on the findings, the research team developed a LED roadway luminaire specification in coordination with VDOT to facilitate LED implementation.

The cost-benefit analysis of the VDOT project assumed a service life of 100,000 hours or 25 years for LED luminaires. It evaluated three scenarios: replacing all current HPS luminaires at once, replacing all HPS luminaires in a five year period, and replacing in 10 years. The results suggested that the investment in LED luminaires would be returned in eight years for all scenarios, although the five-year scenario corresponded with the shortest investment return time. Over the life time, the return-on-investment (ROI) for the different scenarios ranged between 3.25 and 5.76. In terms of energy consumption, all three scenarios would cut the lighting energy cost by half during the 25-year analysis period compared with the scenario where no LED technology would be used. Replacing HPS luminaires with LED technology would also result in savings in maintenance and related costs (including HPS lamp replacement costs) between 16-19% over a 25-year period.

This paper presents part of the findings of the VDOT study, with a focus on technology comparison and implementation considerations at STAs. The paper also includes guidelines for STAs when developing LED roadway luminaire specifications.

METHODOLOGY
This project involved a comprehensive evaluation of sample LED roadway luminaires for a two year period. The major activities involved in the project included:

- Identification and selection of LED luminaires,
- Conduct initial laboratory test of the selected luminaires,
- Conduct a two-year field test of the selected luminaires,
- Conduct second laboratory test of the selected luminaires,
- Gather VDOT lighting-related inventory and expenditure information,
- Conduct life-cycle cost-benefit analysis, and
- Develop a LED roadway luminaire specification.

The following sections describe in detail the methods used for research activities relevant to this paper, including the selection of LED luminaires, laboratory tests, and field tests.

LED Luminaire Selection
Based on previous research experience and VDOT recommendations, the research team contacted a list of reputable LED lighting vendors to acquire sample systems for evaluation. At the end of the process, the research team selected five different LED luminaire designs and obtained six luminaires for each of the designs. For benchmarking purposes, the research team also obtained three traditional 250 W HPS luminaires. Among the obtained luminaires, two of
each type were assessed in detail in the laboratory and field tests. The remaining luminaires were installed in the field and observed for their stability and long-term performance. TABLE 1 lists the LED systems evaluated during this project followed by pictures of the luminaires in FIGURE 1.

TABLE 1 Luminaires Evaluated during This Project

<table>
<thead>
<tr>
<th>Design</th>
<th>Mfg. Year</th>
<th>Mfr. Rated Watt</th>
<th>Mfr. Rated Lumen</th>
<th>Weight (lb)</th>
<th>Qty.</th>
<th>LED Design Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>HPS</td>
<td>03/2012</td>
<td>250</td>
<td>-</td>
<td>25</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Design A</td>
<td>04/2012</td>
<td>195</td>
<td>4452</td>
<td>25</td>
<td>6</td>
<td>Exposed LED optic array</td>
</tr>
<tr>
<td>Design B</td>
<td>2012</td>
<td>120</td>
<td>8985</td>
<td>25</td>
<td>6</td>
<td>Three-panel folding design with large LED sources</td>
</tr>
<tr>
<td>Design C</td>
<td>05/2012</td>
<td>148</td>
<td>-</td>
<td>45</td>
<td>6</td>
<td>Three large LED sources with conventional layout</td>
</tr>
<tr>
<td>Design D</td>
<td>2012</td>
<td>150</td>
<td>9285-13890</td>
<td>25</td>
<td>6</td>
<td>Exposed, elongated LED optic array</td>
</tr>
<tr>
<td>Design E</td>
<td>08/2011</td>
<td>200</td>
<td>-</td>
<td>32</td>
<td>6</td>
<td>Exposed LED optic array</td>
</tr>
</tbody>
</table>

FIGURE 1 Lens design of evaluated LED and HPS luminaires.
Luminaire Testing Methodology
After obtaining the luminaires, the VTTI team performed the initial laboratory evaluation of the luminaires to compare the different LED luminaire designs with each other and with HPS. The initial testing entailed mounting two sample luminaires (labeled No. 1 and No. 2) of each manufacturer in a laboratory facility for an initial “burning-in” time of approximately 100 hours and then installing the luminaires individually in an outdoor VTTI testing facility for detailed performance assessment. After the initial laboratory test, the luminaires were tested in the field for two years. At the end of this process, the research team retrieved the luminaires and conducted final laboratory testing for comparison with the initial laboratory test results. Both initial and second laboratory tests followed the same procedure.

The VTTI outdoor testing facility consisted of a light pole fitted with an adjustable bracket that could accommodate most luminaire types. The research team defined a measurement grid extending 6 m behind, 13 m in front of, and 20 m to each side of the luminaire (FIGURE 2). Luminaires were mounted at a height of 30 ft. (9.1 m), considering that a majority of conventional roadway luminaires at VDOT are installed at a height between 30 and 45 ft. (9.1 and 13.7 m).

During laboratory testing, the research team measured:

- Horizontal illuminance, measured with a Konica Minolta™ T-10 illuminance meter mounted on a mobile device at the pavement level, facing up, at the center of each cell in the 20 x 40 m grid.
- Vertical illuminance, measured using a Konica Minolta T-10 illuminance meter mounted 1.5 m from ground level (approximately the height of the eyes of the driver of a regular passenger vehicle) on a mobile device. Measurements were taken at the center of each grid cell.
with the meter positioned vertically perpendicular to the roadway direction and facing the grid centerline.

- Light trespass, measured as vertical illuminance along the front and back edges of the grid with the meter vertically in parallel with the roadway direction and facing the luminaire side.
- Electrical power usage, measured with a Yokogawa WT 110 power meter. The research team waited at least 15 minutes after an LED luminaire was powered on before taking each measurement to avoid the potential effects of in-rush current. For each HPS measurement, the research team waited at least 30 minutes after the HPS luminaire stabilized.
- Correlated Color Temperature (CCT), measured with a Konica Minolta CL-500 Illuminance Spectrophotometer measured directly beneath each luminaire.
- Spectral power distribution (SPD), measured using an Ocean Optics S4000 spectroradiometer with a Teflon integrating sphere acceptance optic. The research team only measured the relative irradiance as the interest was the relative power concentration by wavelength. To facilitate comparisons, the SPD results for different luminaires were normalized to the same scale.

During the field evaluation, all sample luminaires, including both LED and HPS systems, were installed in a park-and-ride facility (VDOT designated lighting testbed) at a standard height of approximately 35 ft. (10.6 m) between September 2012 and September 2014. The facility was located in the middle of a large wooded area with minimum interference of environmental lighting from adjacent roadways and commercial and residential developments. The luminaires were operating every night from dusk to dawn, equivalent to a total operational period of approximately 8,800 hours.

The research team conducted field measurements at three-month intervals, for a total of nine rounds of data collection. During each visit, the research team collected vertical illuminance, horizontal illuminance, and CCT following the same procedures as used during the laboratory tests but over a smaller grid measured 12 m x 36 m. The research team also conducted visual inspections for dirt buildup and wildlife intrusions, luminaire temperature recording (ballast and LED components), and an observation of the luminaires’ installation condition.

Collecting horizontal and vertical illuminance measurements over a large grid required a large number of readings for each luminaire, which was extremely time-consuming. To improve efficiency and accuracy, the research team developed an automated data acquisition application in the National Instruments® LabVIEW software environment. During the data collection, the automated application collected continuous illuminance readings from the illuminance meter for two seconds at each location and then wrote the mean illuminance into a comma-separated values (CSV) file. To enable real-time data validation, the application interface included measurement visualization windows as well as buttons that allowed values to be redone or deleted upon faulty measurements.

During both laboratory and field tests, the research team took multiple ambient horizontal and vertical illuminance measurements before and after each data collection. The hourly temperatures during each data collection were later obtained for the nearest weather station from the National Oceanic and Atmospheric Administration (NOAA). During data analysis, all
outdoor measurements of the LED systems were corrected based on ambient horizontal and vertical illuminance levels. In addition, all LED illuminance measurements were normalized to a standard temperature (i.e., 25°C) assuming that a reduction of each degree Celsius in ambient temperature coincides to a light output increase by 0.25%. All analyses used only measured data instead of software simulated information.

TECHNOLOGY COMPARISON

**Horizontal Illuminance**
Laboratory testing results suggested that the LED luminaires evaluated provided lower levels of mean horizontal illuminance over the VTTI laboratory grid compared to the HPS luminaires (FIGURE 3). However, light output of the HPS systems concentrated in a relatively limited area, suggesting poor performance in achieving light uniformity (FIGURE 4). Note that, although the lighting level at the focal area of HPS luminaires are much higher than that of the evaluated LED luminaires, much of the illuminance is wasted in reality since lighting applications are typically designed for a larger area and controlled by minimum illuminance/luminance values.

![FIGURE 3 Average laboratory horizontal illuminance over VTTI lab grid.](image-url)
Overall, the different LED designs exhibited very different horizontal illuminance distribution patterns, with Design E more oval and elongated (i.e., Illuminating Engineering Society [IES] Type II [9]) while Design A, B, and D more circular yet widespread (i.e., similar to IES Type IV distribution). Notice that the horizontal illuminance patterns of Design A, B, and D luminaires had irregularly shaped peak areas instead of being circular or oval (FIGURE 4). The Design C LED luminaires with large LED light sources resembled the light distribution (i.e., IES Type III) of the HPS systems more than other LED designs. The different light distribution patterns suggest that a clear understanding of the horizontal illuminance pattern of a LED luminaire is critical for developing the most cost-effective lighting design for a specific application.

**Vertical Illuminance**
The HPS luminaires provided a higher level of mean vertical illuminance over the VTTI laboratory grid than the LED luminaires. However, the HPS systems provided highly concentrated vertical illuminance levels within the close vicinity of the luminaire (FIGURE 5), resulting in relatively intensive glare and poor vertical illuminance uniformity. Most LED designs (e.g., Design A, B, D, and E) provided a much more uniform distribution of vertical illuminance. In addition, the rear trespass levels of LED luminaires (along the outmost grid line behind the luminaire) was all found to be lower than the HPS luminaires (FIGURE 6). Lower light trespass levels are a desired feature for most roadway lighting applications to avoid light pollution and reduce energy waste. Among the different LED luminaire designs, Design A and D luminaires (with long, narrow optic arrays) had the highest light trespass levels.
Spectral Power Distribution and Correlated Color Temperature
All LED luminaires evaluated emitted light that is much closer to natural light in color. The HPS luminaires emitted yellowish lights with high special power distribution within the 490 – 510 nm (green) and 560 – 620 nm (yellow) ranges (FIGURE 7). On the other hand, all the LED luminaires demonstrated high light concentration around 450 nm (blue). This resulted in significant color differences between the LED luminaires and the HPS systems, with the former resembles the color of natural light much better while the latter appearing yellower.
FIGURE 7 SPD curves for evaluated LED and HPS systems.

The manufacturer-rated CCTs for the evaluated luminaires were 4300 for Design A, 5000±300 for Design B, and 4000 for Design C, D, and E. The field and laboratory testing results suggested that the CCTs for Design D luminaires were within the close range of the manufacturer-rated value. The measured CCTs for other luminaires, on the other hand, fell out the ranges (significantly in some cases) allowed by ANSI C136.37 (10). In addition, the CCTs for tested luminaires decreased over the two-year period by 2 – 8%, with Design B decreasing by 8.1%, Design A by 5.5%, and Design E by 4.2%.

Light Loss and Light Quality Deterioration
Based on the initial and second laboratory testing results, the LED luminaires had a 6% overall reduction in light output after two years due to lumen and dirt depreciation, compared to the 10% (for horizontal illuminance) or 3% (for vertical illuminance) reduction for the HPS systems. All LED designs experienced comparable light loss between vertical and horizontal illuminance. However, the considerably different loss of horizontal and vertical illuminance for the HPS systems indicated that dirt accumulated on the lenses of HPS systems (including a significant amount inside the lenses due to lack of ingress protection [IP]) reflected part of the light output, which had more significant impact on horizontal illuminance. The field measurements also suggested a mild light loss for the LED systems over the two-year study period (FIGURE 8).
Power Consumption and Efficacy
The measured wattages of most LED luminaires were consistent with manufacturer ratings with the only exception of Design D LED luminaires (17% variance). The measured efficacies of most LED luminaires were comparable to that of the HPS systems, with Design C luminaires slightly exceeding the HPS systems. The mean measured efficacies based on horizontal illuminance were 0.06 lux/W for Design A luminaires; 0.08 lux/W for Design B, D, and E luminaires; 0.10 lux/W for Design C luminaires; and 0.09 lux/W for HPS luminaires. Efficacy in this context is defined as the ratio between measured illuminance and luminaire power.

LED ROADWAY LUMINAIRE SPECIFICATION CONSIDERATIONS
One of the major objectives of this project was to develop a well justified LED roadway luminaire specification for use for VDOT Lighting projects. The comprehensive evaluation of the selected LED systems provided knowledge that served as the basis of the VDOT specification and is valuable to other STAs in the process of developing or updating their LED roadway luminaire specifications. This section summarizes a number of guidelines for developing specification requirements at STAs based on the major findings of the project.

Luminaire Lens Design
This study showed that light distribution patterns of the different LED designs can be significantly different, with both desired and unfavorable light distribution characteristics. Some LED designs (e.g., Design A, B, and D) had irregularly shaped contours in horizontal illuminance distribution, which may result in difficulties during lighting design. These results suggest that it is necessary to clearly define the required light distribution type when developing LED roadway luminaire specifications or selecting LED luminaires for a specific lighting application.

The field test suggested that luminaire lenses with exposed optic arrays did not attract more dirt than those covered with larger lenses during the first two years of operation, although it was more difficult to clean individual optics in the field. Considering that many LED luminaires may stay in service for multiple decades, STAs may consider to require LED luminaires with optic arrays to be covered with larger smooth lenses to facilitate lens cleaning during routine maintenance.

Correlated Color Temperature
The test results suggested that the measured CCTs mostly fell out the range allowed by ANSI C136.37. In addition, some luminaires experienced considerable CCT decreases over the two year study period (i.e., more than 5% for Design A and B). Due to the fact that the luminaires were only studied for two years, it is not clear if the CCT change trend would continue for a longer period and if it would follow the same decreasing trajectory (i.e., near linear based on this study). Readers should notice that, ANSI C136.37 classifies a CCT of 5000 and above as cool white, 4000 - 4500 as neutral white, and 3500 and lower as warm white. If the observed CCT decrease lasts longer following the same trajectory, it is possible for a cool white luminaire to become neutral white or for a neutral while luminaire to become warm white within a matter of a years. Based on this finding, STAs may consider tying the allowed CCT decrease over time to warrantee requirements.
Luminaire Housing Construction
The housings of most evaluated LED luminaires did not have sufficient IP. During the two-year field test, the research team found wildlife intrusion and dirt buildup inside many luminaire fixtures (FIGURE 9). In addition, significant corrosion was found in some housings constructed of metal materials (FIGURE 9B). These results strongly indicate that sufficient IP protection (e.g., IP65 according to ANSI C136.25 [11]) for luminaire housings is necessary to protect the luminaire electrical components throughout their entire service lives. The results also suggest that sufficient corrosion control measures need to be used for luminaire housings constructed of metal materials. The researchers did not find issues with the optical assembly ingress protection for any of the LED designs.

Ease of Installation
All studied luminaries were designed to slip-fit onto a two-inch tenon with one- or two-piece clamps mounted using two or four hex bolts. During this project, the research team found that, while meeting vibration requirements, luminaires relying on two hex bolts required more careful installation/uninstallation in the field, especially when the bolts did not have mechanisms to prevent over extraction. In addition, all luminaires had clamps with smooth surfaces. As a result, luminaires that were not securely fastened rotated around the tenon after they were installed in the field for a period of time. Based on these results, STAs may consider requiring all luminaire fixtures to have at least four bolts at the tenon insertion with mechanisms for bolt over extraction. The surface of the clamps that is in contact with the tenon should be serrated to prevent rotation after installation. The luminaires should also have a mechanism to allow incremental vertical tilt adjustment to adapt to different applications.

Technical Specification Sheets
During this project, the research team noticed that the technical specification sheets of different LED luminaires did not follow a standard format. As a result, it was difficult to identify certain key technical specifications for the luminaires (e.g., weight, effective projected area [EPA], lumen ratings, color rendering index [CRI], and/or operational temperature range). In addition, many manufacturers used the same specification sheets for a series of projects, making it extremely difficult to identify the correct information for a specific model. Some specification sheets even contained obsolete/outdated information. When developing an LED roadway luminaire specification, the STA may also require the manufacturer to provide standard, up-to-date specification sheets that include all required technical parameters for the specific model submitted for bidding.
Labeling
Currently, there is no standard for internal labeling style and contents of LED roadway luminaires. Some manufacturers follow ANSI C136.25 (12) while others don’t. As a result, it is difficult to identify key performance parameters such as CCT, CRI, EPA, weight, wattage, and/or lumen from the luminaires. In addition, labels made of regular paper are subject to significant damages due to corrosion (see FIGURE 9B). Therefore, STAs may include their own internal label requirements pertaining to the content, format, and material in their LED roadway luminaire specifications.

CONCLUSIONS AND RECOMMENDATIONS
During this study, the research team conducted an in-depth evaluation of five different LED roadway luminaire designs and compared their performance with traditional HPS luminaires. The evaluation involved laboratory tests and a two-year field assessment. The study provided knowledge towards a better understanding of the LED roadway lighting technology, which is valuable for many STAs in the process of implementing the technology statewide. Many of the findings also served as the basis for developing a practical and forward-looking LED roadway luminaire specification at STAs.

- The LED luminaires outperformed HPS systems in light quality. Overall, the LED systems exhibited better light uniformity, but different LED designs showed considerably different lighting distribution patterns. All LED luminaires evaluated emitted light that was much closer in color to natural light. In contrast, the HPS luminaires emitted yellowish light with high special power within the 490 – 510 nm (green) and 560 – 620 nm (yellow) ranges. Most evaluated LED luminaires also exhibited a much more uniform horizontal and vertical illuminance distribution. In addition, all LED luminaires evaluated showed a lower level of light rear trespass than the HPS systems.

- The light output of LED systems decreased during the first two years, but not significantly when considering performance variation and ambient factors. Laboratory testing results showed that the LED luminaires had 6% less output after two years of operation due to light loss and dirt depreciation. In addition, the CCTs for all LED luminaires decreased over the two-year period.

- LED fixtures need to be properly installed and have proper ingress protection. Data analysis and visual inspection results suggested that, without proper installation procedures and/or mechanisms, luminaires could fail to meet leveling and orientation requirements during operation. Many evaluated luminaires did not have housings with sufficient ingress protection, resulting in significant rust/dirt accumulation and wildlife intrusion inside the electrical compartment.

Based on this project, the research team recommends the following to facilitate the implementation of LED technology at STAs:

- Establish an LED luminaire prequalification and testing program. For each lighting project, there can be potentially a large number of products submitted for bidding. Understanding and testing these products requires significant expertise and in many cases is considerably time-consuming. To ensure that only suitable and reliable products are submitted for bidding, an LED prequalification program should be established to identify and characterize
existing LED products meeting STA requirements. Such a program would reduce the technical and liability burden for contractors and project managers within tight project schedules, and therefore reduce project delays. It would also minimize the possibility of using faulty products for VDOT projects by allowing more expertise in product selection and more time for thorough product testing.

- Develop and maintain a lighting inventory in the current/future asset management framework. With the more widespread use of LED luminaires, it becomes more critical to develop and implement a statewide lighting inventory system to manage, store, and track the LED roadway luminaires and related technical and design data. LED luminaires are relatively expensive, with long service lives (e.g., 10 – 25 years), varying in photometric performance (e.g., different light distribution type and CCT), rapidly improving (e.g., old models become unavailable in a few years), and warranted for a long period. Without an accurate and up-to-date lighting inventory system, STAs may have difficulties tracking service lives of the luminaires against their warranties. In addition, the department will likely lose original lighting design and technical files, resulting in difficulties in selecting replacement luminaires. A good lighting database will also provide long-term institutional memory for project quality and energy consumption.

- Update LED roadway luminaire specifications frequently to reflect the latest technology status. Roadway LED lighting technology is rapidly improving. In the near future, many of the LED products on the market today will no longer be available. Various new products with significantly improved performance will emerge, rendering many established performance metrics obsolete. As an example, most LED luminaires acquired in 2012 for evaluation in this project were already not in production in late 2014 according to the vendors the research team contacted.

- Continuously monitor the performance of different LED luminaires to better understand the technology. This research was based on results from a two-year study, which did not allow sufficient analysis of LED performance change over time. It will provide a great opportunity for STAs to continuously track the performance of the LED luminaires for a much longer period of time as they start implementing the technology. Such continuous performance monitoring will provide critical knowledge for STAs to update the LED specification and lighting design standards/processes. The research team recommends that STAs continuously monitor the field performance of LED luminaires for at least 10 years.

- Develop training for project managers and VDOT lighting engineers. The LED roadway lighting is a relatively new arena and requires considerable knowledge to identify the most suitable products and design the most cost-effective applications. This has posed a challenge for some project managers and lighting engineers who do not have sufficient experience with the large variety of LED luminaires and their different performance metrics. The research team recommends STAs develop and deliver periodic training courses to relevant personnel regarding LED luminaire characteristics and best practices in LED roadway lighting design.

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