Illuminating
ENGINEERING SOCIETY

IES RES-1-16

Measure and Report Luminaire Dirt Depreciation (LDD) in LED Luminaires for Street and Roadway Lighting Applications

MEASURE AND REPORT LUMINAIRE DIRT DEPRECIATION (LDD) IN LED LUMINAIRES FOR STREET AND ROADWAY LIGHTING APPLICATIONS

Final Report prepared for the

Illuminating Engineering Society of North America

January 2016

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INTRODUCTION

Light-emitting diode (LED) luminaires present new challenges for those maintaining outdoor- and roadway-lighting systems. In other luminaire types, maintenance crews often clean the luminaires when they do a bulk or single relamp (Illuminating Engineering Society of Australia and New Zealand (2012)), so the lamp life drives the cleaning schedule. However, LED-based luminaires are being marketed as lasting longer and requiring less maintenance than other luminaire types. As a result, they will be exposed longer to environmental dirt and other contaminants that can adhere to the luminaire and reduce the amount of light that reaches the road. This creates a different maintenance paradigm for LED luminaires, and their potential for dirt depreciation should be carefully investigated. The effect of dirt on luminaire output has long been studied, but past research was conducted on older designs that did not use LEDs. Complicating the problem is that LED luminaires are manufactured in a variety of ways, with different sources, lenses, and ingress protection.

This project sought to quantify luminaire dirt depreciation (LDD) in a number of different types of LED luminaires. This final report discusses project objectives, approach, and methods, presents research results, discusses the results in the context of today's changing roadway lighting environment, and makes recommendations to stakeholders in roadway lighting regarding LDD for LED luminaires.

LIGHT LOSS FACTORS

To ensure that a lighting system meets the minimum light-level requirements at the end of its life, lighting engineers calculate how much light will be lost during the course of a luminaire's operation and compensate for that loss by increasing the levels of illumination in the initial design. The two greatest light-loss factors used for predicting lumen loss over time are lamp or LED lumen depreciation (LLD) and LDD. LLD is non-recoverable without replacing the lamps or, in the case of LEDs, the "light-engine" of the luminaire. LDD, however, is a recoverable loss. Thus, this project considered dirt depreciation on roadway LED luminaires.

Predicting LDD

LLD is predictable. Manufacturers should provide reliable values for calculating the LLD of their products. LDD, on the other hand, has traditionally been difficult to estimate because of the wide variety of environments, lamps, and luminaire types used in outdoor lighting. Although standards for estimating LDD have evolved over time, they still remain inadequate for outdoor lighting in general and LED luminaires in particular.

Early Work in LDD

Today's LDD values for outdoor lighting are based on research performed prior to 1970 in offices or at industrial sites (Siminovitch, Hamilton, Zhang, and Verderber (1993)). In a seminal paper that remains the basis for LDD estimates to this day, Clark (1963) combed through data from thousands of readings of luminaires before and after they were cleaned, where the time between cleanings was known. He placed the luminaires into six categories based on their rate of dirt accumulation. Clark's (1966) follow-up article repeated his initial recommendations for calculating LDD. Despite the limitations of Clark's research, it has remained the most in-depth study of LDD for decades and was the basis for the 1984 *IES Lighting Handbook's* recommendations.

The American National Standard Practice for Roadway Lighting (Illuminating Engineering Society of North America 2000), or RP-8, simplifies the procedure in the 1984 and 2000 *IES Lighting Handbooks*. The RP-8 states that the LDD for roadway lights should be calculated by selecting the atmospheric condition (very similar to Clark and the IES *Handbooks*) and cleaning cycle, and using the provided chart to find the LDD value. The chart provided is very similar to the chart for Category I (no top or bottom enclosure) in the 2000 *IES Lighting Handbook*. The United States Environmental Protection Agency (1995) also produces a handbook for lighting maintenance that recommends calculating LDD based on the curves in the 1984 and 2000 *IES Lighting Handbooks*.

The CIE has also produced guidelines for calculating LDD but refers to it as the "luminaire maintenance factor." The CIE 154:2003 (International Commission on Illumination 2003) for outdoor lighting maintenance states that engineers should calculate the luminaire maintenance factor by identifying the luminaire's IP(Ingress Protection) rating, the pollution category (high, medium, or low) of its environment, and its exposure time between cleanings. That information is used to look up the luminaire maintenance factor in a reference table. Unlike the IES standards, the CIE quantifies the pollution categories based on particle levels in the atmosphere and accounts for the current ability to produce luminaires with higher IP ratings. Other standards, for example BS 5489-1:2003 (British Standards Institution 2003), use the table from the CIE 154:2003. The CIE standards are based on data from the 1980s (Sanders and Scott 2007).

Recent Work in LDD

A leading manufacturer of outdoor lighting fixtures states that one of their outdoor luminaires has an open ventilated design to minimize dirt depreciation (2014). A manufacturer of LED luminaires stated that they design their roadway-lighting luminaires to be maintenance free by using smooth, non-porous acrylic lenses and mesh or open tops, thus allowing dew and rain to naturally remove dirt or debris (Schlitz (2014)). Another avenue for natural cleaning is a combined effect from the vortex flow from passing vehicles and wet environments causing water to splash against the luminaire.

Key to the ability of a material to self-clean by dew or rain is the ability to shed the water before it evaporates. Materials with a high water contact angle are called hydrophobic; those with a low contact angle are hydrophilic. Water will shed from hydrophobic surfaces more easily than hydrophilic surfaces, therefore hydrophobic surfaces are considered self-cleaning (Marmur, 2003). Clean glass has a relatively low contact angle of 25–29 degrees (Texas, 2015), while PMMA (acrylic, Plexiglas) has a contact angle of 70.9 degrees (Enterprises, 2015). Based on contact angle, acrylic should be better at self-cleaning than glass. However, there are coatings, such as Rain-X®, that can be added to the surface of glass that make it more self-cleaning.

New research has also brought the CIE standards into question. Sanders and Scott (2007) stated that the pollution categories in BS 5489 (and the equivalent table in CIE 154:2003) are a source of error in LDD calculations. They surveyed municipalities in the United Kingdom and found that more used the "medium" pollution category than would be expected, and that most cleaned their luminaires at intervals of three years or longer. They also tested luminaires with an IP65 rating or better in open areas in the three pollution categories. The luminaires were carefully packed to not dislodge the dirt and then sent to their manufacturers for testing before and after cleaning. Results indicated that all the luminaires tested had less LDD than would be predicted using the BS 5489 values. Additional results showed that in urban areas luminaires mounted higher than 8 m had lower and more consistent levels of dirt depreciation.

Light Distribution and LDD

No research was found that reported light distribution as part of LDD measurements, but a few studies mentioned it. The CIE 97:2005 (International Commission on Illumination 2005), in Section 3.4, states that dirt deposits on a luminaire will affect its light distribution, but the document does not specify how the light distribution will be affected. Sanders and Scott (2007) stated that they collected data on light distribution as part of their study on LDD, but they did not report those data. Siminovitch, Hamilton et al. (1993) stated that, "if dirt is deposited non-uniformly over the lamp and interior fixture surfaces, the relative candlepower distribution may change slightly, reducing the accuracy of nadir candle power [their measurements] alone as an indicator of the fixture's changing lumen output," but argued that their approach was sufficient to draw conclusions about dirt depreciation on vented versus non-vented compact fluorescent lamps (Siminovitch et al., 1993, p. 5).

In previously unpublished, related work from a small investigation performed by the authors, a 400-W HPS luminaire was removed from the Virginia Smart Road for photometric characterization. After photometric measurements were performed, the luminaire was cleaned and the measurements repeated. The results, shown in Figure 1, indicate that the dirt depreciation was greater at the edges of the luminaire's area of illumination than directly beneath the luminaire. The tested luminaire was a flat-lensed type II medium throw, and a significant portion of its light distribution is projected at low angles through the edge of the glass. These low angles would be more significantly impacted by the dirt on the lens, and the throw of the luminaire would be diminished more there than in the central area. These results indicate that the application of a single factor for dirt depreciation is fundamentally incorrect, because dirt depreciation does not affect light distribution uniformly.

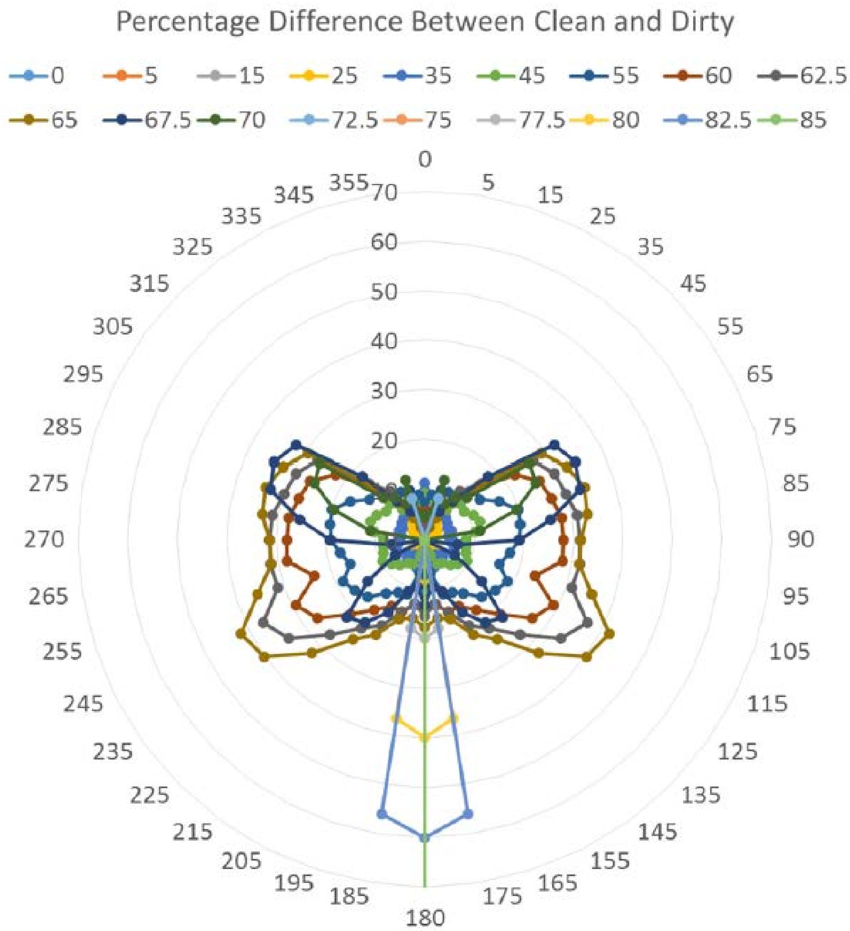


Figure 1. Photometric dirt depreciation polar distribution showing non-uniform LDD.

LED LUMINAIRES AND DIRT DEPRECIATION

LED luminaires create a new paradigm for roadway luminaire maintenance. They do not need to be maintained as frequently as other luminaire types, and they have longer service lives, so dirt depreciation has the potential to greatly affect their performance at end of life. Additionally, "LED luminaires" do not form a single category that will perform uniformly with respect to dirt depreciation because the optical components of LED luminaires vary significantly from one luminaire to another. Some luminaires are more traditional, with light sources and reflectors behind a glass panel (Figure 2a). Other LED luminaires use internal reflection, aiming the individual LED sources, and using individual lenses on each LED source to distribute the light (Figure 2b). Those optical elements may or may not be sealed behind another optical element (Figure 2c). Some optical elements may include many small prisms built into the outer surface to spread out the source of the light to reduce glare. All of these light distribution features result in different LDD distributions, possibly requiring different LDD factors for different luminaires.

(a) (b) (c)

Figure 2. Different configuration of LED luminaire optics: (a) molded acrylic refractive and reflective optics over multiple LED sources with a flat glass outer optic; (b) individually molded refractive acrylic optics over each LED source with no outer optic; (c) individually molded refractive acrylic optics over each LED source with a flat glass outer optic.

Evaluations of Installed LED Luminaires

LED luminaires have been installed and studied in a number of environments. In Brazil, LED luminaires were installed to replace high pressure sodium (HPS) luminaires in a metropolitan park, and in Boston LED luminaires took the place of fluorescents in a bridge application (Curran and Keeney 2006, Rodrigues, Almeida et al. 2011). Despite their widespread use, though, there appears to be no guide specific to LED luminaire maintenance. Leotek, an LED luminaire manufacturer, has created a municipal guide for converting to LEDs (Leotek n.d.). They state that there is little field data on cleaning LED luminaires, but that LED luminaires are less hot than other luminaire types, that dust is therefore less likely to adhere to them, and that a lower LDD is expected. They do not suggest new LDD values, though, and advise municipalities to measure the illuminance of their LED luminaires and clean them if the illuminance drops more than 10%.

Survey of LED Optical Configurations

Commercially available LED luminaires were also surveyed. The list is not reproduced here, only the summary data. This was accomplished by researching manufacturers and their respective catalogs for LED luminaires recommended or known by the team to be installed for roadway illumination. This survey was reasonably conclusive for the state of the art at the time of the literature review. The team found 24 LED luminaires used for roadway lighting. Luminaires specific to tunnel and garage lighting were not included. A summary of the LED optical configurations is shown in Table 1. LED roadway luminaires can be grouped into six categories (Table 1) based on the optical configuration.

Table 1. LED Roadway Lighting Luminaire Categories based on Optics Type

Types of LED Luminaires		
Percentage of Luminaires	**LED Optics**	**Luminaire Optics**
50%	Individual molded acrylic	None
17%	Molded acrylic	Flat glass
17%	Individual molded acrylic	Flat glass
8%	Molded glass	None/white reflector
4%	Large individual molded acrylic	None
4%	Individually molded polycarbonate	None

Cleaning LED Luminaires

A number of manufacturers of LED roadway luminaires recommend various cleaning procedures. These are presented in Table 2 and sorted by the luminaires' optical material.

Table 2. Manufacturers' LED Luminaire Cleaning Recommendations

Manufacturer	Model	Optical Material	Recommended Cleaning Procedure (per Manufacturer Documentation or Representative)
Dialight	StreetSense	Glass	"Cleaning is not a normal practice for these fixtures."
GE	Evolve LED Roadway Light	Glass	To maintain high efficiency of the lens, occasional cleaning of the outer lens surface may be needed, with frequency dependent on local conditions. Use a mild soap or detergent, which is essentially neutral pH (pH approximately 6 to 8), nonabrasive, and which contains no chlorinated or aromatic hydrocarbons. Wash thoroughly, using a soft cloth. Rinse with clean, cold water and wipe dry.
LED Roadway Lighting	NXT	Glass	No recommended cleaning procedure. Some customers use a hose and water, but it is up to the customer.

Manufacturer	Model	Optical Material	Recommended Cleaning Procedure (per Manufacturer Documentation or Representative)
Cooper	Cobrahead LED Luminaires	Acrylic	A regular maintenance schedule should be followed to retain optimal light output and thermal performance. Optical lens cleaning should be performed with a clean dry cloth to remove any dust or other contaminants. Additional cleaning can be performed with non-abrasive acrylic cleanser. Remove any dirt, leaves or other foreign debris from the housing and fins. Clean water may be used to flush the fins.
Cree	LEDWay fixtures; Fixtures with NanoOptic lenses	Acrylic	The manufacturer states that “LEDway fixtures are designed to be near maintenance free and therefore do not include an operational/maintenance guide” but follows up with: “If you feel cleaning is necessary, the following care should be provided when cleaning the luminaire. Using water wipe the luminaire with a sponge or soft brush recommended for safe use on automobile finishes. You may also use a mild dish detergent in water if desired. Rinse with water (if using a pressure washer the pressure that the luminaire is being exposed to at the point of contact should be similar to that of a typical garden hose connected to a local utility water supply). If more cleaning is desired, a hose down cleaning or cleaning with mild soap would be acceptable.”
LED Roadway Lighting	SAT-M	Acrylic	No recommended cleaning procedure. Some customers use a hose and water, but it is up to the customer.
Lighting Science	DBR, Type III, LSR4 NW R3, 150W	Acrylic	No particular procedure recommended. It can be sprayed with a hose or cleaned with other procedures that will not damage the acrylic.

There was some concern expressed by manufacturers over the use of isopropyl alcohol (IPA) on optics. One luminaire manufacturer states that 100% IPA is not compatible with acrylics and polycarbonates (AcuityBrands 2015). However, PALRAM industries states that polycarbonate is resistant to IPA (PALRAM 2015). In addition, ePlastics (ePlastics 2015) describes the compatibility of acrylic with IPA as “Fair” with some effect after 7 days of constant exposure at 20°C.

Polycarbonate is listed as having limited resistance to detergent (PALRAM 2015), while AcuityBrands lists detergent solution as not being compatible for either plastic in one document (AcuityBrands 2015) but lists carwash detergent and soap suds as compatible with both kinds of plastic. Therefore, it is not clear whether mild detergent, such as dish washing detergent, is compatible or not with the plastic optics.

LITERATURE SUMMARY

Although light loss factors and luminaire dirt distribution have been studied and measured for decades, current methods for determining LDD in outdoor and industrial settings appear to be outdated. There is little data on the effect of dirt on a luminaire's light distribution, or on dirt depreciation in LED luminaires, which have the potential to save a great deal of energy. However, to fully appreciate the efficiency and lighting quality of LED luminaires, careful lifetime performance measurements need to be performed to ensure that LED luminaires meet their minimum lighting levels at their end of life.

OBJECTIVES

The primary objective of this research was to determine the LDD for various types of LED luminaires in the field. This research sought to characterize LED luminaire performance for various luminaire optics types, luminaire materials, luminaire IP ratings, and luminaire installation environments.

A secondary objective was to specify an optimal cleaning method for LED luminaires that was safe and efficient to perform in the field, and that adequately cleaned the luminaires.

DATA COLLECTION EXPERIMENTS

Since there has not been a conclusive study of LED luminaire deprecation, the team developed a two-part experiment to collect data with regard to different LED luminaire optics. The first experiment was a pilot study on the Virginia Smart Road. The second data collection experiment was performed at four different sites: Hampton, Virginia; Minneapolis, Minnesota; Charleston, West Virginia; and Woodbridge, Virginia. Due to faults in the data collection, the data from Woodbridge were not usable. However, there were two locations in Charleston, West Virginia, that were of different age and different luminaire optic types. Finally, data from a concurrent, related laboratory study of dirt depreciation on LED luminaires funded by the Virginia Department of Transportation (VDOT) and performed by the authors was included in the analysis.

APPROACH

Experimental Order and Rationale

The project was divided into two experiments. A pilot experiment tested LED luminaire cleaning methods on roadway luminaires on the Virginia Smart Road. The pilot experiment identified the most practical and effective cleaning method before the team attempted to clean LED luminaires in the field. During the pilot, the team took before and after photometric measurements from the LED luminaires to gain a preliminary understanding of the possible scope of LDD.

The second experiment was similar to the pilot. The team took photometric measurements of LED luminaires in situ in four locations before and after cleaning, but only the most effective cleaning method was used, and measurements were performed on public roadways open to traffic. The second experiment was performed at four locations and included LED luminaires of 10 designs. During one in situ experiment, the team revisited the cleaning methods due to concerns of compatibility of the plastic optics with the IPA. Measurements for the second experiment were constrained by the need to stay on the roadways illuminated by the luminaires. The luminaire designs are designated with arbitrary letter designations in the descriptions and in later data analysis.

Data from a concurrent related VDOT study were included to expand the age of installations and to take advantage of a larger number of data points per luminaire. During this related project, 11 luminaires of five designs, one of which was the same as a design as one of the in-situ designs, were removed from their points of installation and transported to the Virginia Tech Transportation Institute (VTTI). Care was taken to maintain the luminaire’s orientation to minimize the disturbance of the dirt. The luminaires were then carefully mounted on a pole in an outdoor laboratory, and photometric measurements were taken on a grid. They were then cleaned using the most effective cleaning method identified during this study, and photometric measurements were retaken.

Locations

Five locations were chosen for the study: the Virginia Smart Road; Charleston, West Virginia; Hampton, Virginia; Minneapolis, Minnesota; and Woodbridge, Virginia.

Virginia Smart Road

The pilot study testing was performed on the Virginia Smart Road, a 2.2-mi closed experimental highway equipped with a variety of luminaire types mounted on luminaire poles at 80-m intervals (Figure 3).

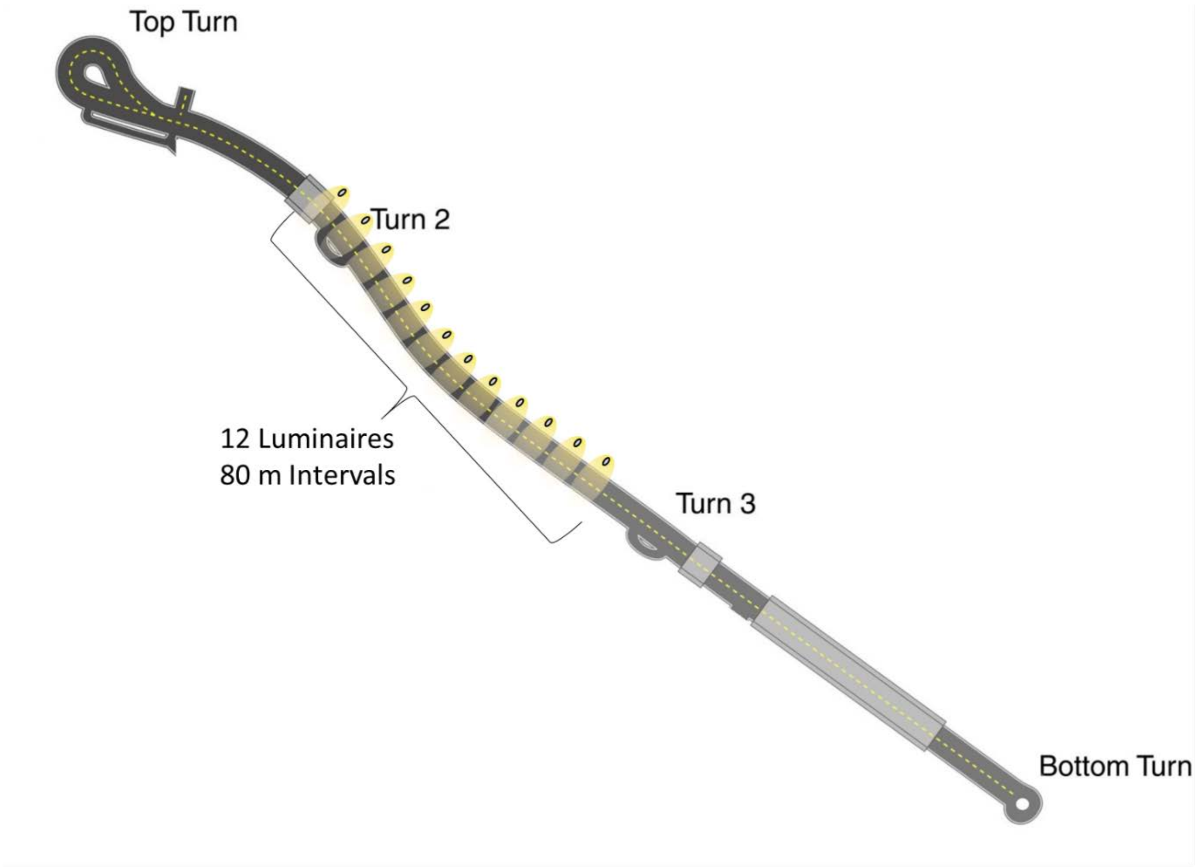


Figure 3. Location of luminaires on the Virginia Smart Road.

The Virginia Smart Road is equipped with two sets of LED luminaires from a single manufacturer. These luminaires have a type II light distribution pattern and differ only in correlated color temperatures: 3500K and 6000K (Figure 4). The luminaires, designated type A, were installed approximately six years prior to this experiment, and were not cleaned during that time. An overhead photo of the location is shown in Figure 5.

Figure 4. Virginia Smart Road LED luminaires.

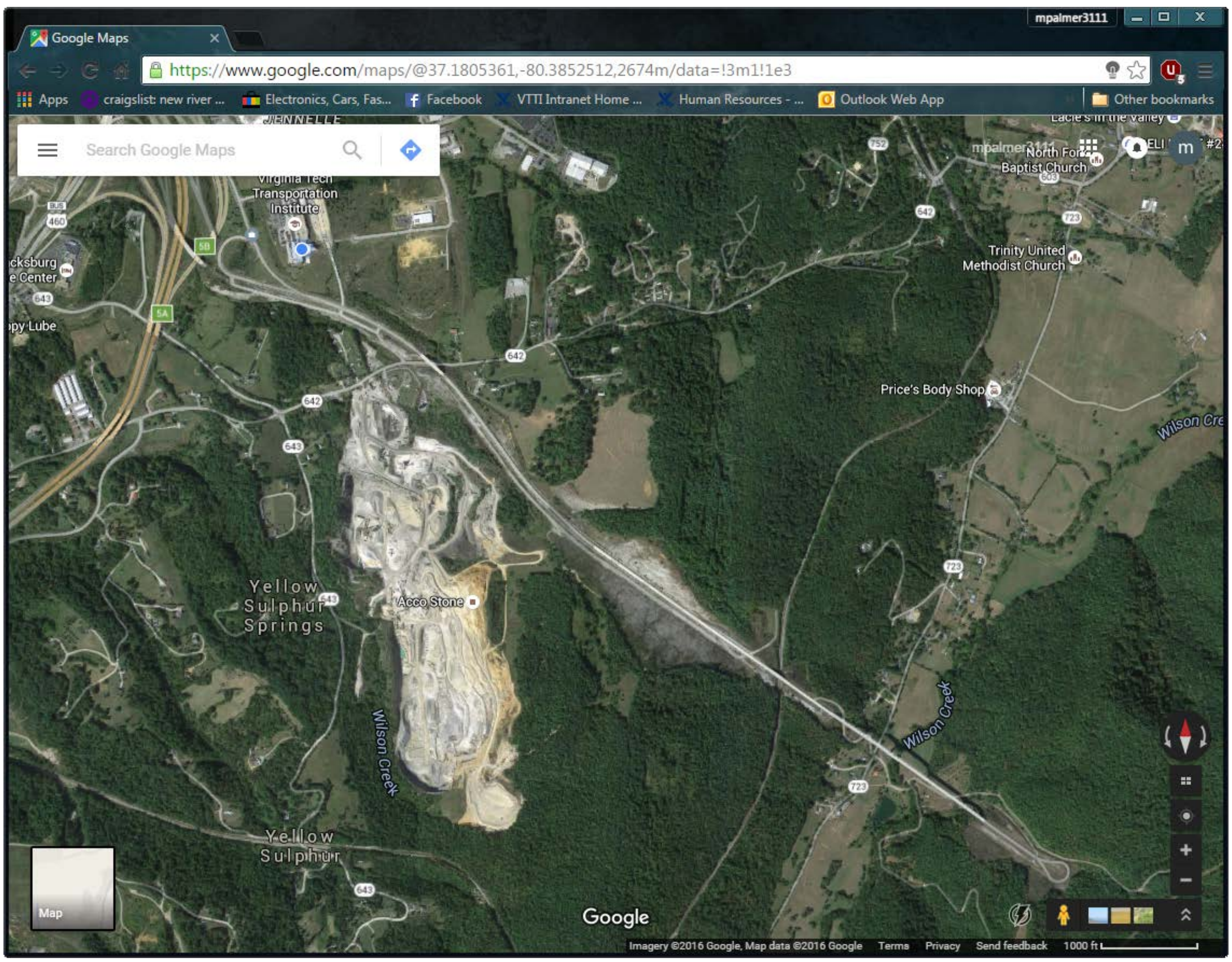


Figure 5. Overhead photo of Virginia Smart Road.

Charleston, West Virginia

The Charleston, West Virginia, location was selected for the variety of LED luminaires installed, especially the molded glass optics. Figure 6 and Figure 7 show the two LED installations (circled in white) in West Virginia that the team used in the field study of dirt depreciation. Several miles of WV-61 have molded glass optic luminaires installed, and four of the units were installed on I-77. The I-77 installation was installed first and is approximately 5 years in age. The WV-61 luminaires were installed in 2011, making their age approximately 4 years. The section of I-77 with LED luminaires (between exits 98 and 99) averaged 68,500 vehicles per day over the period 2010–2013. The section of WV-61 used for the study averaged 22,000 vehicles per day.

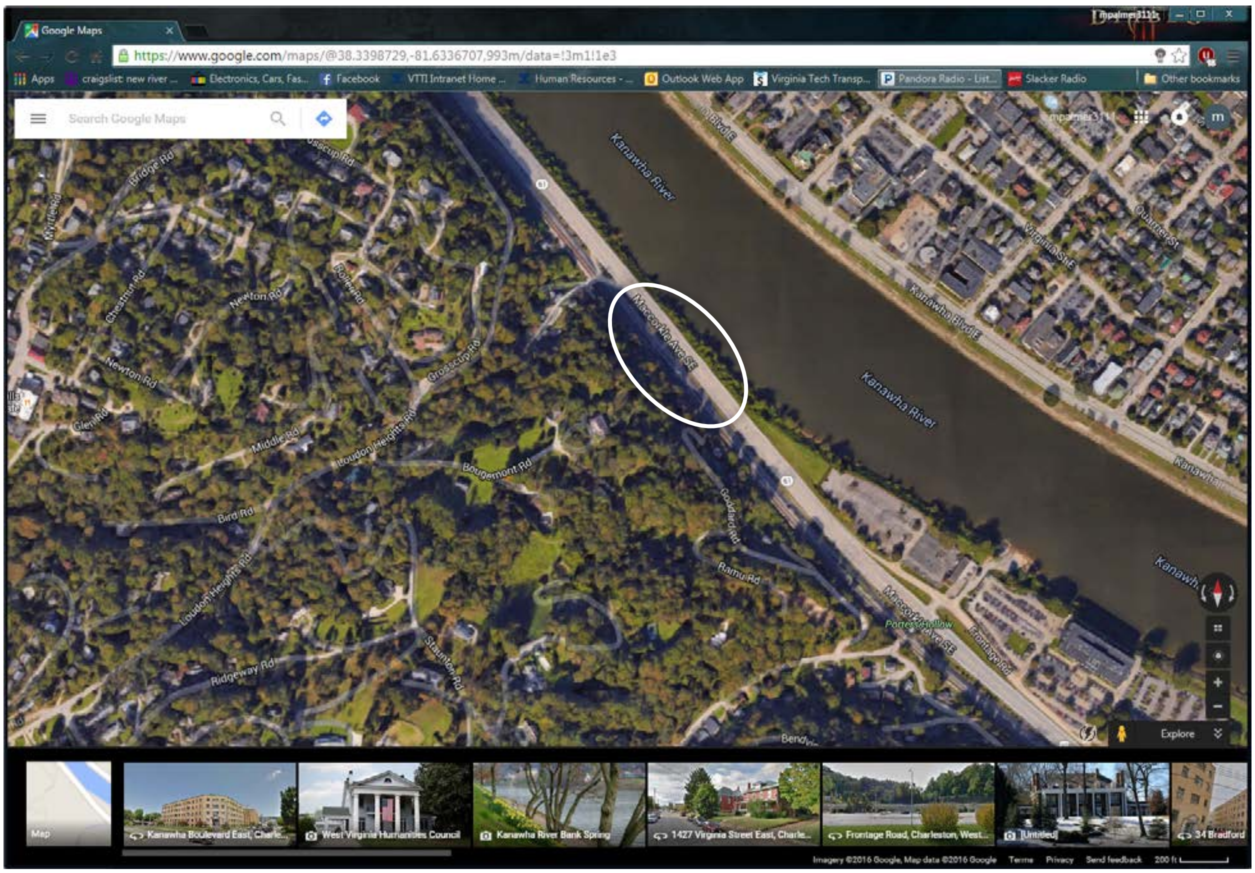


Figure 6. WV-61 LED luminaire installation.

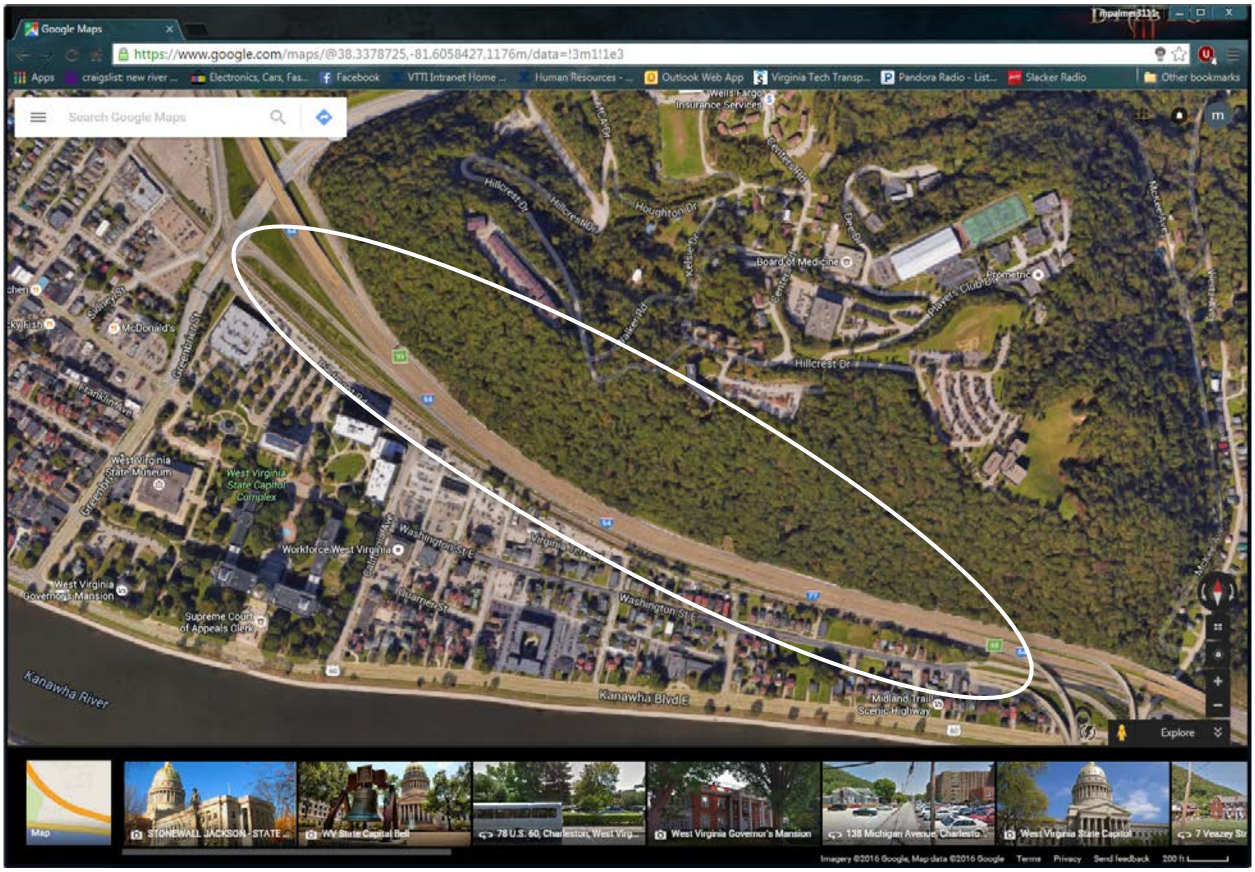
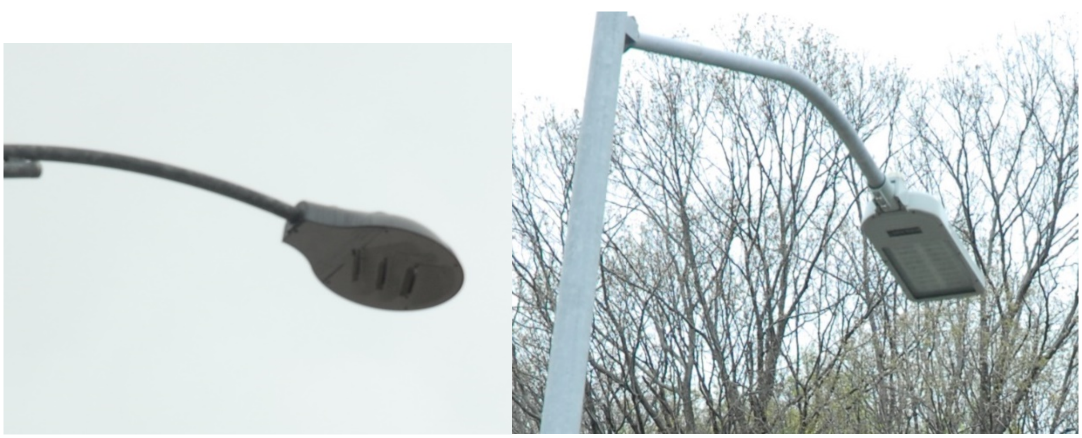


Figure 7. I-77/I-64 LED luminaire installation.

On I-77, five types of led luminaires were installed: type F (Figure 8a), type G, type J (Figure 8b), type K (Figure 9) and type L. Only the F luminaire was used on WV-61. All of this work, cleaning included, was performed at night at this location due to lane closure restrictions set by the West Virginia Department of Transportation (WV-DOT).



(a) **(b)**

Figure 8. Installed LED luminaires in Charleston, WV: (a) type F; (b) type J.

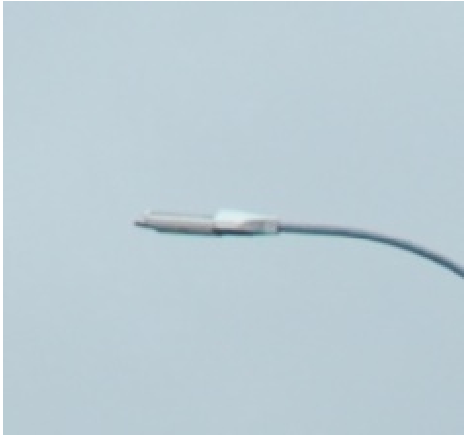


Figure 9. Type K LED luminaire in Charleston, WV.

Unfortunately, the I-77 location was not ideal in terms of light pollution. As shown in Figure 10, the northbound lanes are elevated above the southbound lanes, with HPS luminaires mounted in-between the lanes. The light from these luminaires was not able to be eliminated. However, we were able to isolate the light from one luminaire that was relamped during the study. The overall effect of the HPS contribution to the LED illuminance measured was minimal and on the same order as the noise in the data.

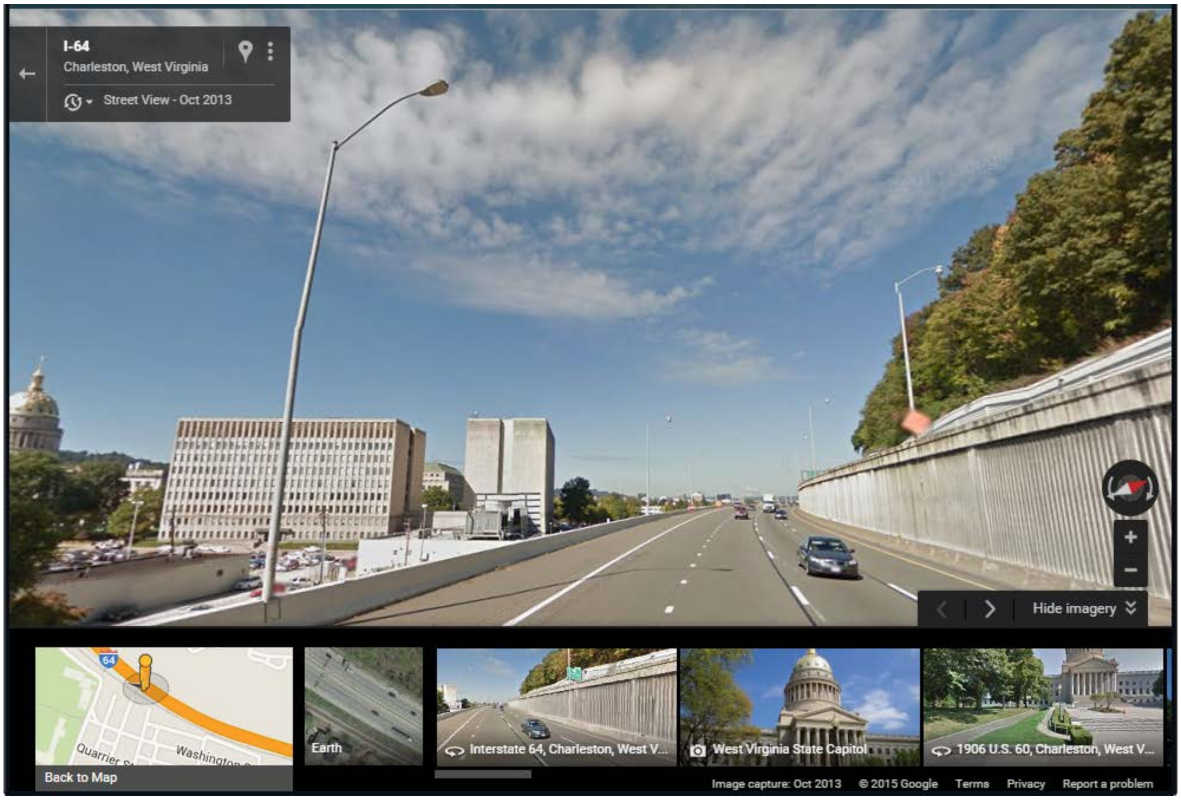


Figure 10. Street view of LED luminaires on I-77 with proximity to HPS lighting.

Hampton, Virginia

The Hampton Roads Bridge-Tunnel north island was selected for its exposure to salt spray (Figure 11). The luminaires are not installed directly over the highway. Instead, they are installed in the tunnel support area around the entrance and exit of the northbound and southbound lanes of I-64. The traffic volume for all lanes of traffic averaged 86,000 vehicles per day. However, it is not clear if the full effect of the traffic affects the dirt accumulation at this location. The installation age is 3 years.

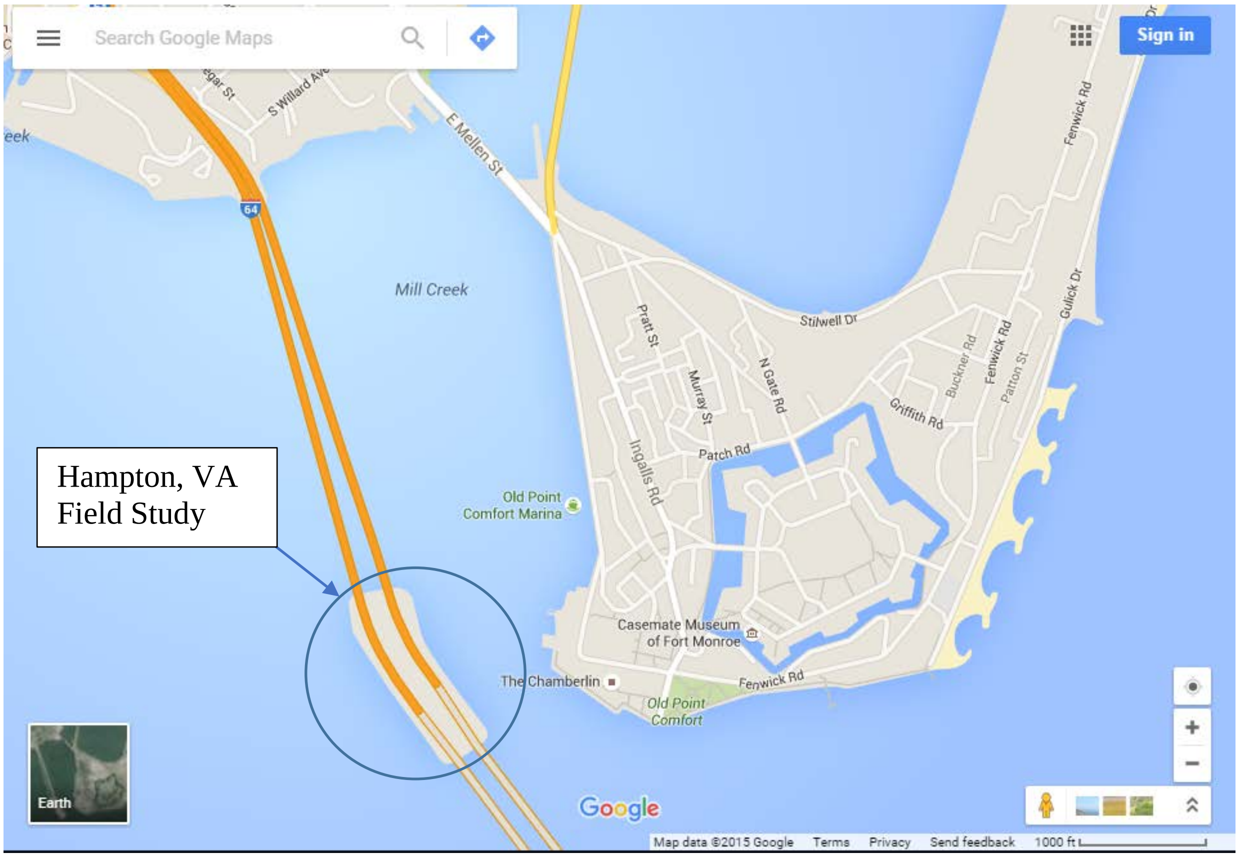


Figure 11. Map of Hampton Roads Bridge-Tunnel.

Figure 12 shows the luminaire installation as seen from an overhead photograph of the north island. The team not only used this installation for the in situ measurements, but also revisited the cleaning method during this field visit to study mild detergent solution as an alternative to 70% IPA.

As illustrated in Figure 12, three luminaires on either side of the northbound lanes of I-64 were cleaned with detergent solution and three luminaires on either side of the tunnel were cleaned with 70% IPA. It was assumed that salt spray would be the major contributor of dirt on these luminaires, so the team wanted to clean luminaires with both cleaning methods on the side edge of the island to provide comparative data for salt-spray conditions.

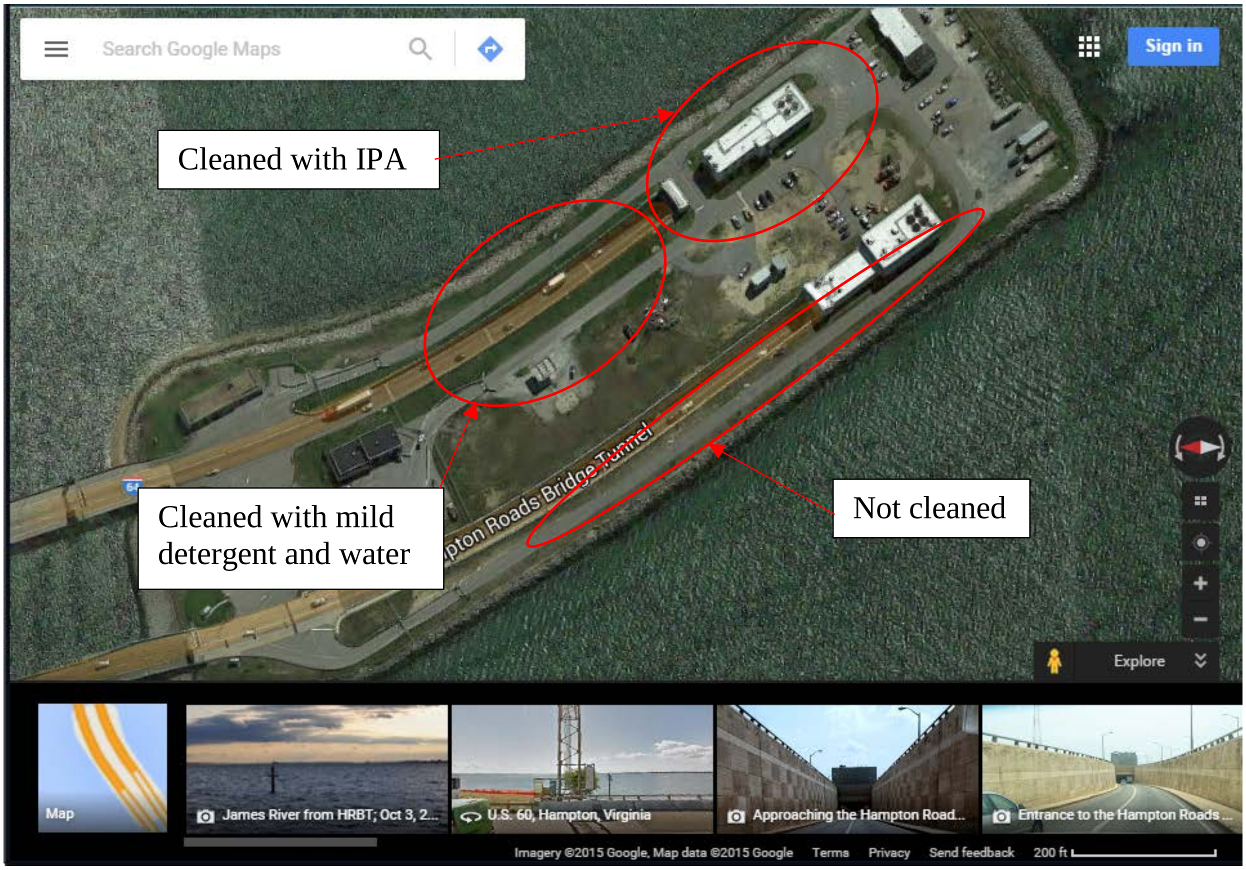


Figure 12. Cleaning plan for Hampton study area.

Figure 13 shows the type of LED luminaire installed, which is very similar to those installed on the Virginia Smart Road and comes from the same manufacturer. Figure 14 shows the installation of the luminaires on the island.

Figure 13. LED luminaire installed at Hampton bridge site.

Figure 14. Hampton LED installation.

Minneapolis, Minnesota

The I-35W bridge in Minneapolis was completed in 2008, giving the LED installation an age of 7 years when cleaned (Figure 15). This bridge saw a traffic volume of 280,000 vehicles daily (DOT 2013). This site was chosen for its traffic volume and the age of the installation. In addition, the Minnesota Department of Transportation (MNDOT) uses salt (sodium chloride and magnesium chloride) during the winter, so these luminaires are exposed to salt, dirt, soot, and hydrocarbons. Figure 17 shows the VTTI team preparing to clean the I-35W luminaires after collecting the illuminance data the night before. In Figure 18, a VTTI researcher can be seen wiping the luminaire clean with IPA and a microfiber cloth.

The luminaires installed at this location are from the same manufacturer as the luminaires installed on the Virginia Smart Road and are very similar in design (Figure 16).

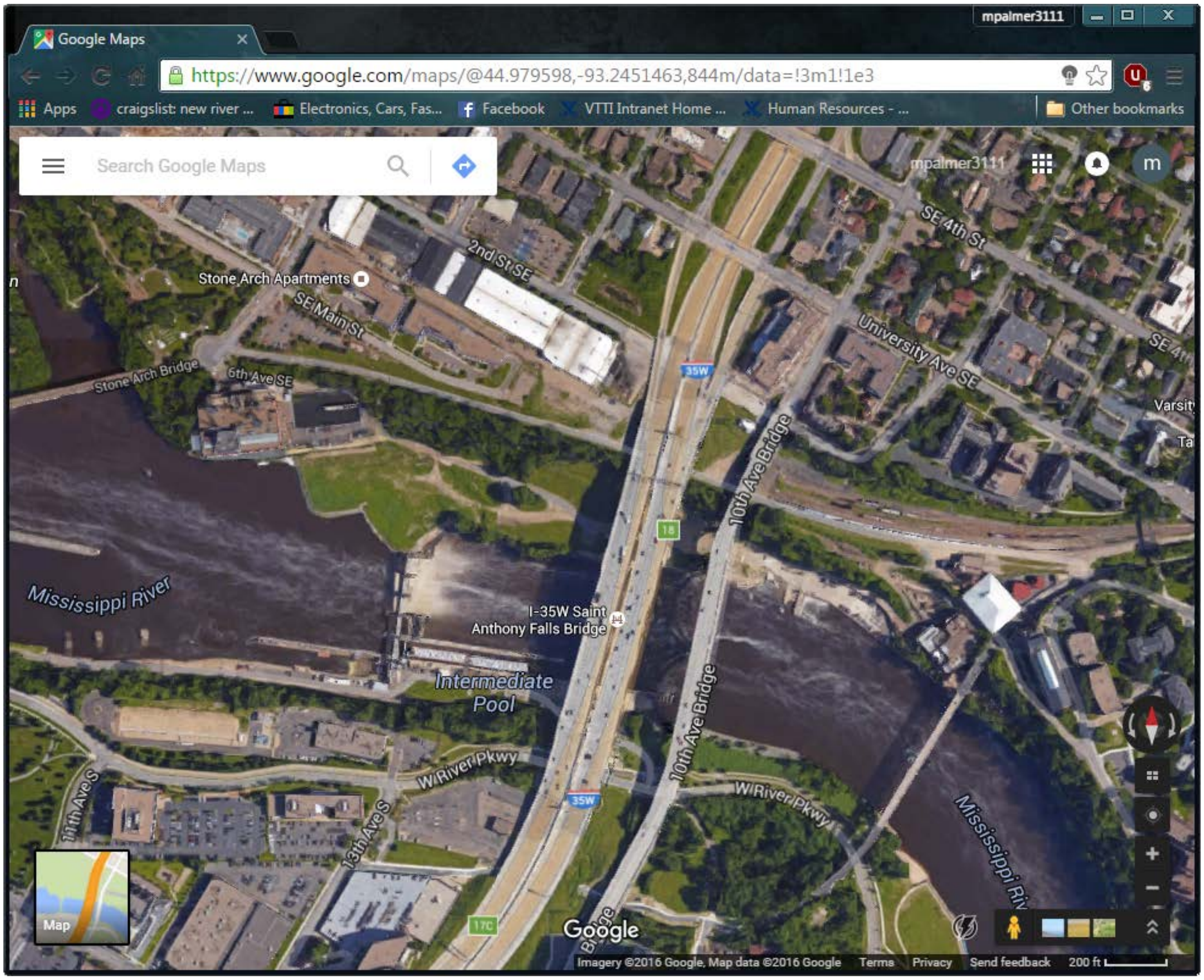


Figure 15. I-35W bridge in Minneapolis, MN.

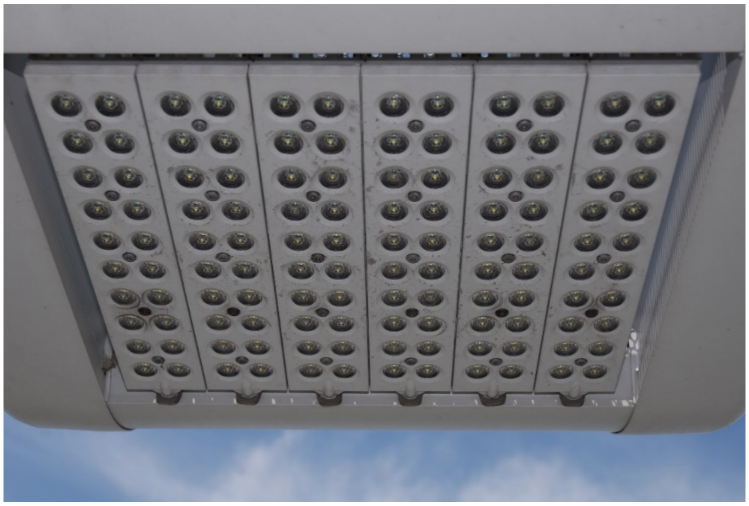


Figure 16. Minnesota LED luminaires.

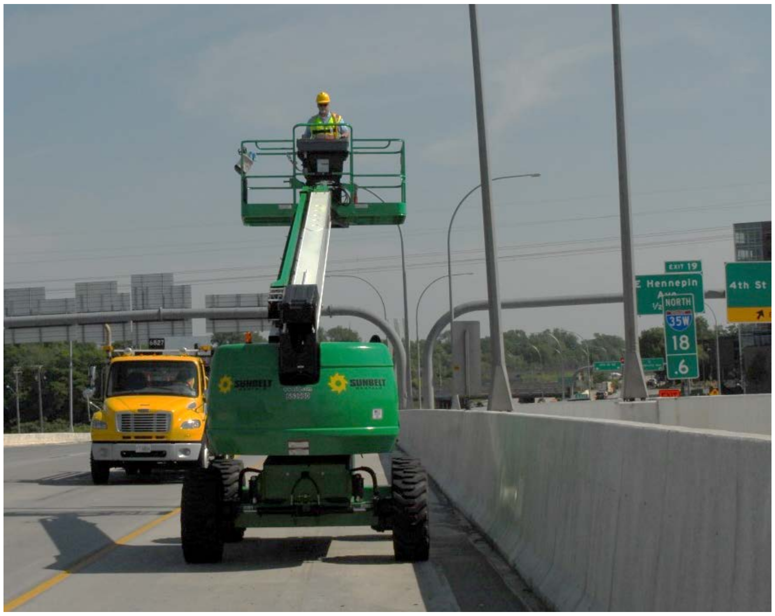


Figure 17. I-35W luminaire cleaning, showing MNDOT lane closure and man lift used.

Figure 18. Cleaning an I-35W luminaire with IPA wipe.

Woodbridge Parking Facility, Woodbridge, Virginia

This parking facility was used by VDOT to test several LED luminaires to develop a specification for LED roadway lighting (Figure 19). The team traveled back to this facility and performed an in situ experiment consisting of measuring illumination, cleaning the luminaries, and remeasuring the illumination for the luminaires that had not been taken down for laboratory measurement. At the time of the data collection and cleaning, the luminaires had been installed for 3 years. This facility had a variety of luminaires installed (Figure 20). In Figure 20 the luminaire marked as Design A is the same model as the one installed on the Virginia Smart Road.

Unfortunately, due to data collection system errors, these data were not usable. The team therefore mined and reanalyzed the laboratory data collected for VDOT (Ronald Gibbons 2015) for inclusion in the in situ analysis of dirt depreciation.

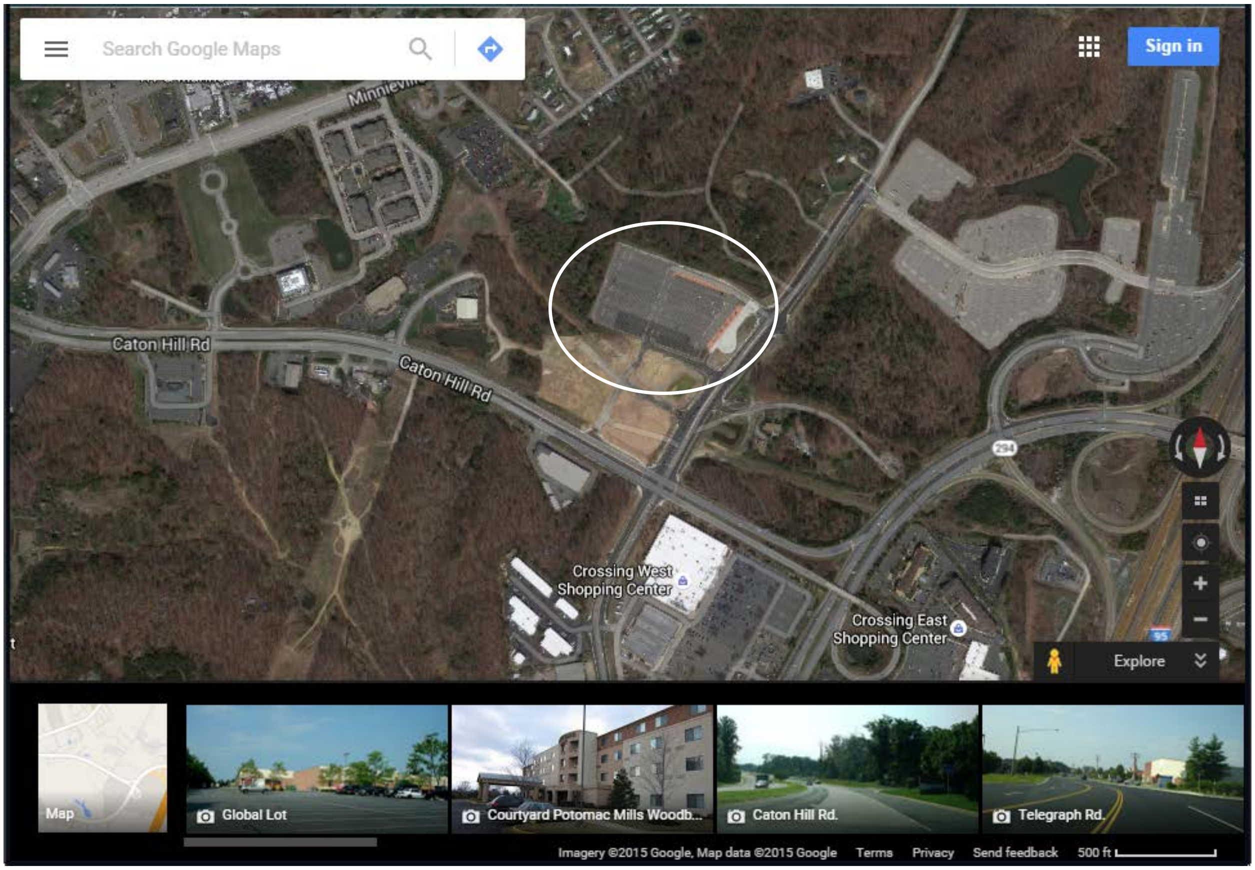


Figure 19. Satellite photo of Woodbridge Park and Ride lot.

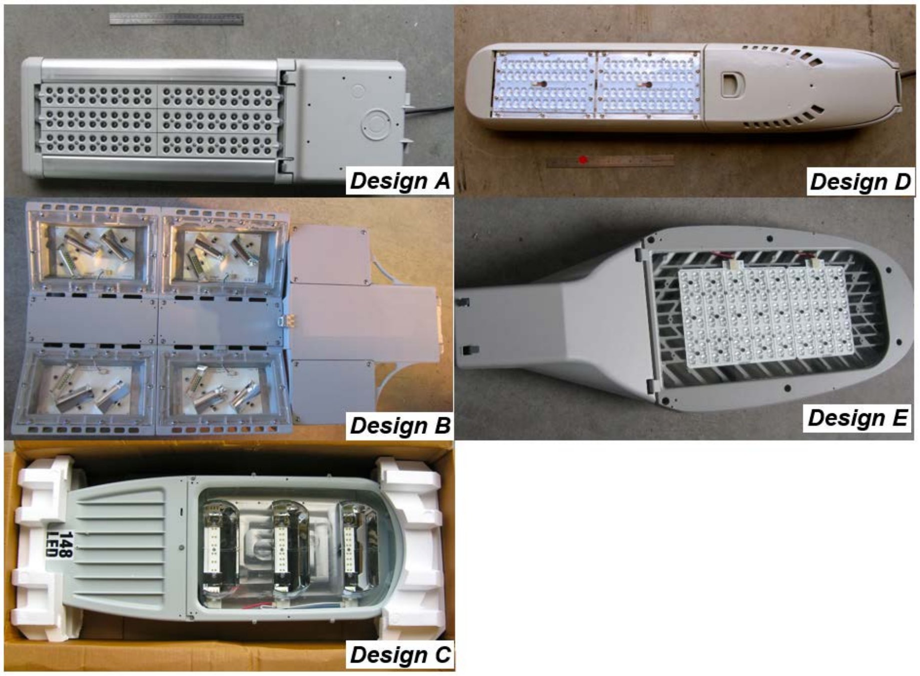


Figure 20. LED luminaires used at the Woodbridge Park and Ride.

Photometric Equipment

For the Smart Road pilot study and in situ study, the VTTI-owned Roadway Lighting Mobile Measurement System (RLMMS), a diagram of which is shown in Figure 21, was used to measure illuminance before and after cleaning. The RLMMS system captures dense, accurate photometric data from a moving vehicle. The RLMMS collects horizontal illuminance, vertical illuminance (glare), as well as roadway luminance, along with corrected color temperature (CCT), and by nature of the measurement, lighting uniformity. It couples the measurements with accurate Global Positioning System (GPS) locations that can be then related to the locations of the luminaire poles. The RLMMS can take measurements along a length of roadway, so other metrics along that roadway can also be measured, such as uniformity, glare, and luminance. The RLMMS was selected because it can take photometric measurements from any roadway, so the luminaires did not need to be removed, a time-consuming, and costly procedure. Removal of luminaires may also disturb accumulated dirt, which may result in inaccuracies in the photometric measurements.

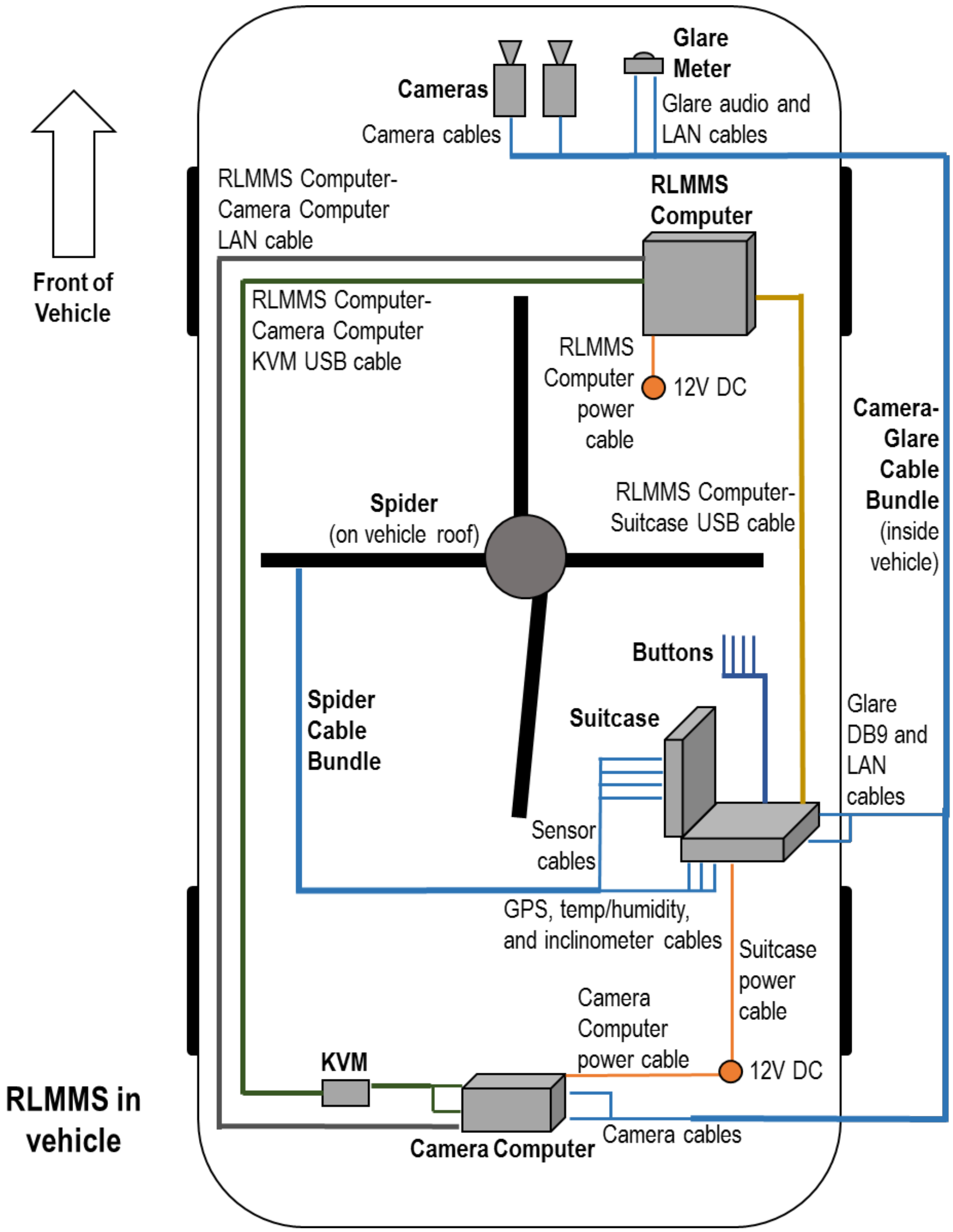


Figure 21. Diagram of RLMMS system.

Other Equipment

Other equipment used included a pressure washer, a variety of bucket trucks, and an aerial boom lift. Various cleaning supplies were used during the pilot experiment to determine the most effective cleaning agents.

SMART ROAD PILOT STUDY

Before going to the field to take photometric measurements, clean the luminaires in situ, and retake the photometric measurement, the team wanted to identify the most practical, safest, and best method to clean roadway luminaires. The team identified potential cleaning procedures based on manufacturer recommendations and tested them on LED luminaires on the Virginia Smart Road. Being a closed research facility, the Virginia Smart Road provided a safe environment for developing the procedures.

METHODS

Procedure

The overall procedure with all of the experiments was to measure the dirty illuminance one night, clean the luminaires, and remeasure the illuminance the next night.

Data Collection

Before and after cleaning, illuminance measurements were taken from the Smart Road using the RLMMS. The RLMMS was placed on the roof of a large sport-utility vehicle (SUV). Measurements were made in each lane and in each shoulder. Measurements were also performed at 20, 30, and 50 mph (33, 50, and 83 km/h). The illuminance was measured on the night preceding the cleaning and then again immediately afterward.

Cleaning Methods

Based on the literature review and survey of manufacturer cleaning methods, the team decided to test the cleaning procedures listed in Table 3. After discussion of various cleaning scenarios, the team settled on a 1-min cleaning time as a reasonable amount of time to clean a luminaire.

A mild detergent solution was initially left out due to concerns raised by there being no definition of a “mild” detergent solution and the incompatibilities listed by some manufacturers. Similarly, 100% IPA was not included because of compatibility concerns. Based on the exposure time of 1 min and a concentration of 70% IPA, it was estimated that the luminaire optics would be exposed to only 0.00694% of the effect reported by ePlastics, which was, for 100% IPA: “Some effect after 7 days of constant exposure to the reagent. Solvents may cause softening, and swelling”. Therefore the team deemed it reasonable to clean the luminaire optics with 70% IPA for 1 min. However, due to concerns over the compatibility of IPA with acrylic and polycarbonate optics, the team revisited mild detergent cleaning during the in situ experiment.

The team attempted pressure washing the luminaires from the ground, but found that the water did not reliably reach the luminaire optics with any kind of cleaning action, even with a nozzle designed for cleaning from a distance.

Table 3. Luminaire Cleaning Procedures

Cleaning Method	Procedure
1	Wipe with a dry microfiber rag
2	Wipe with a microfiber rag wetted with water
3	Wipe with a microfiber rag wetted with IPA
4	Pressure wash the optics from a bucket truck with plain water
5	Pressure wash the optics and the heat sink(s) from a bucket truck with plain water

Cleaning Procedures Using a Rag

Figure 22 shows a team member cleaning a luminaire with a microfiber rag. The procedure in Figure 22 was for Cleaning Method 1 (dry rag), Cleaning Method 2 (wet rag), and Cleaning Method 3 (rag with IPA). For Cleaning Method 2 and 3, the liquid was poured onto the rag, which was then used to wipe the optics. This was followed by a wipe with a dry rag to remove any remaining dirt. The protocol specified spending no more than 1 min cleaning the luminaires. For Cleaning Methods 1, 2, and 3, the cleaning method took approximately 10 min per luminaire, including moving from one luminaire to the next and deployment of the bucket truck.

Figure 22. Wiping the Smart Road luminaires with a rag.

Cleaning Procedures Using a Pressure Washer

The team used a pressure washer with 50-ft pressure hose and a support truck providing water and power to pressure wash the luminaires from the VTTI bucket truck (Cleaning Methods 4 and 5). The pressure-washing setup can be seen in Figure 23.

Figure 23. Setup to pressure wash luminaires on the Smart Road.

It would have been easier to clean the luminaires with a hose form the ground, but the team discovered the water pressure was not sufficient to reach the luminaire. Wind also interfered with the pressure washing, and required the pressure washer be within about 1 ft (0.3 m) of the luminaire, as shown in Figure 24 and Figure 25. This is not recommended by any manufacturer, but was the only way to make pressure washing effective at removing any accumulated dirt. As can be seen, this method requires an additional support vehicle to transport sufficient water to use with the pressure washer, and at least a 50-ft (15-m) hose on the pressure washer. This method took longer than 1 min to clean the luminaire (visually). The overall time to clean a luminaire with Method 4 was approximately 15 min. Method 5 took another 2–3 min, resulting in 17–18 min per luminaire.

Figure 24. Pressure washing the optics of the Smart Road luminaires (Cleaning Method 4).

Figure 25. Pressure washing the heat sink of the luminaires (Cleaning Method 5).

Mild Detergent Solution Cleaning Method

While at the Hampton, Virginia, location, a solution of detergent and water was used to clean six of the luminaires and 70% IPA was used to clean another six. Nine luminaires were left uncleaned. This location was chosen for the additional cleaning study because the luminaires installed here were of the same model and manufacturer as those on the Virginia Smart Road, and because the location would expose the luminaires to significant salt spray.

The detergent solution was initially excluded due to some manufacturers recommending against using it. A few drops of mild dish washing detergent were added to approximately a cup of water (~250 ml). This was shaken until mixed and placed in a pump sprayer like the one used for 70% IPA. The detergent solution was sprayed on the luminaire, then a clean, dry, microfiber cloth was used to wipe off the luminaire. Bottled water was then squirted onto the luminaire to rinse the detergent off. This was followed by another wipe with a clean dry microfiber cloth, and then a third wipe with a third, clean, dry, microfiber cloth to remove any remaining residue. Figure 26 illustrates the rinse step of the water-and-detergent cleaning method. This method required 3 more minutes than the other rag-based cleaning methods, resulting in a total time of 13 min from luminaire to luminaire.

Figure 26. Cleaning a luminaire with water.

RESULTS AND DISCUSSION

Observations

Observations of the Smart Road luminaires before cleaning revealed that some had collected significant dirt (Figure 27).

Figure 27. Dirt accumulated on Smart Road LED luminaire type A (3500K).

Figure 28 shows the dirt left on microfiber rags after they were used to clean a single luminaire using the three cleaning methods requiring a rag. The dirt removed with the dry rag and wet rag was dark grey. The dirt removed with the rag with IPA was more yellow-brown.

Figure 28. Dirt removed from the luminaires with the first three cleaning methods: (1) dry rag, (2) wet rag, (3) rag with IPA.

Figure 29 has photographs of a luminaire before and after cleaning with Cleaning Method 3, a rag with IPA. The luminaire's metal casing appears cleaner, but it is difficult to see a difference on the optics.

Figure 29. Smart Road LED luminaire before (top) and after (bottom) cleaning with an IPA rag (Cleaning Method 3).

Figure 30 shows a close-up of the before and after pictures, where it is clear that there is dirt obscuring the view of the yellow phosphor on the individual LEDs in the before photo (left) that is removed by the cleaning method (right).

Figure 30. Smart Road LED luminaire before (left) and after (right) cleaning with an IPA rag (Cleaning Method 3), clearly showing removal of gray-colored dirt from the optics.

The team pressure washed the heat sink fins successfully, but the design of the heat sink of this particular luminaire trapped the dirty water and did not allow it to drain. The pressure washer was not able to blast all of the dirty water out of the bottom of the heat sink.

Illuminance Data

The data collection was divided into two experiments, one with the 3500K color temperature luminaires (Figure 31) and one with the 6000K luminaires (Figure 32). These figures show the measurement of illuminance as heat maps, where lighter gray indicates higher values, in lux (lx). The measurements are presented on a latitude and longitude grid. The difference between the illuminance before and after the cleaning measures is shown on the same chart displaced downward (south) by 0.0005° latitude. This allows easier spotting of the location of the luminaires by referencing the bright spots in the “after” data.

The boxes in each section indicate each group of two or three luminaires and the cleaning method used. As can be seen in Figure 31, the cleaning methods with the largest effect on the illuminance were the IPA (Cleaning Method 3) and the pressure washing of the optics only (Cleaning Method 4).

Looking at the data in two-dimensional charts (Figure 33 and Figure 34) shows the effectiveness of each cleaning method. The luminaires are mounted on the north side of the smart road. In these charts, right refers to the south side of the road, opposite the luminaires, while left refers to the north side where the luminaires are mounted.

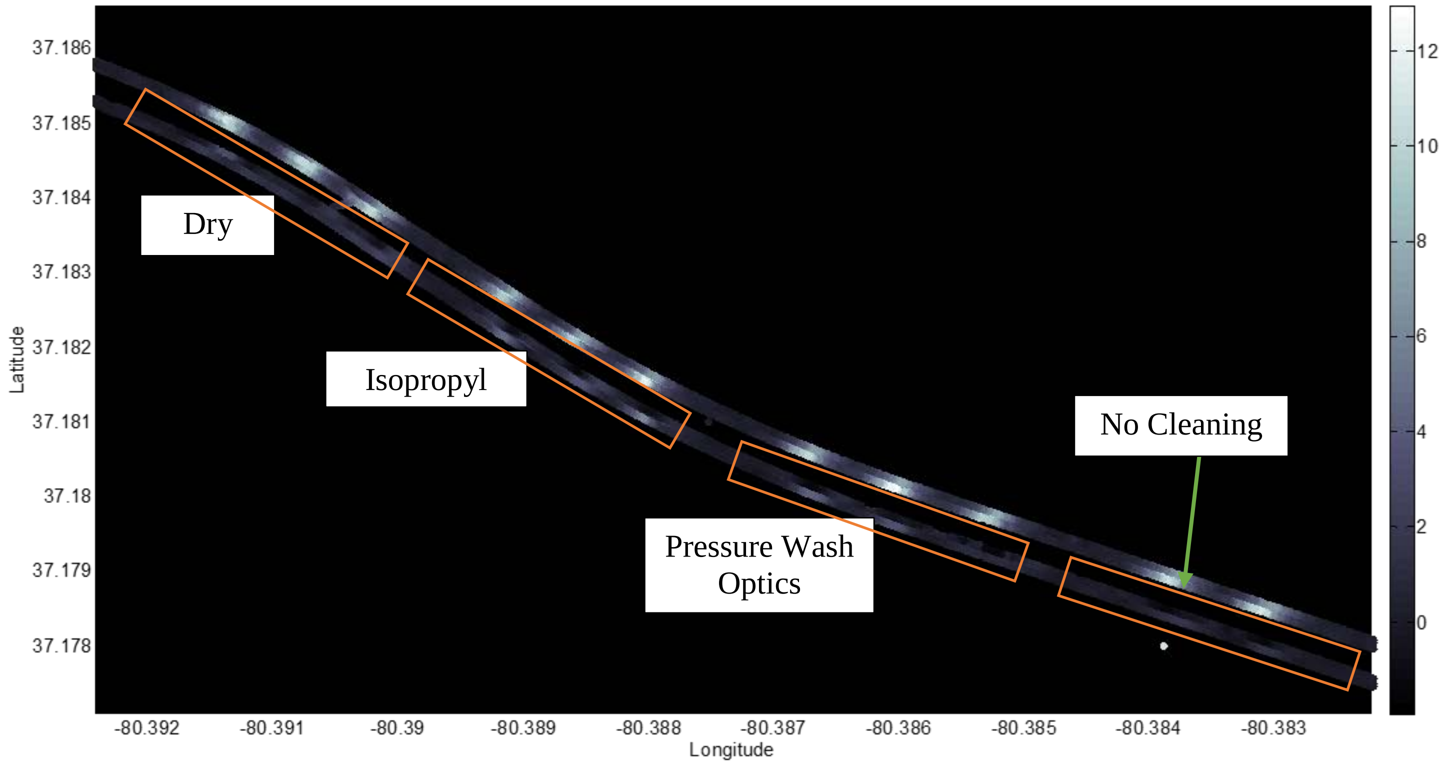


Figure 31. Illuminance vs. latitude and longitude on the Smart Road. Top trace is the illuminance before cleaning. Lower trace is the difference between before and after cleaning. Bottom trace was displaced downward by 0.0005° longitude for display purposes. Gray scale is in lux (lx).

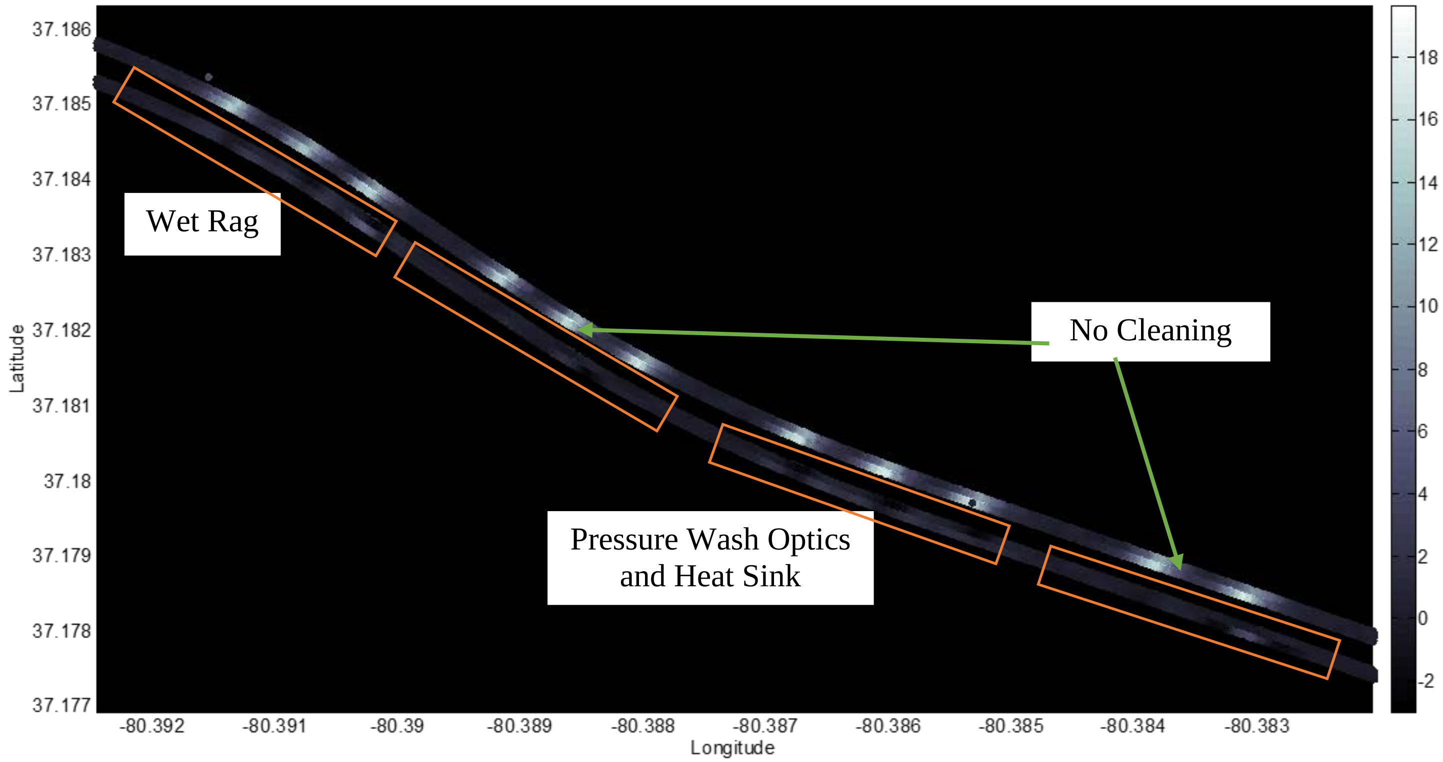


Figure 32. Illuminance vs. latitude and longitude on the Smart Road. Top trace is the illuminance before cleaning. Lower trace is the difference between before and after cleaning. Bottom trace was displaced downward by 0.0005° longitude for display purposes. Gray scale is in lux (lx).

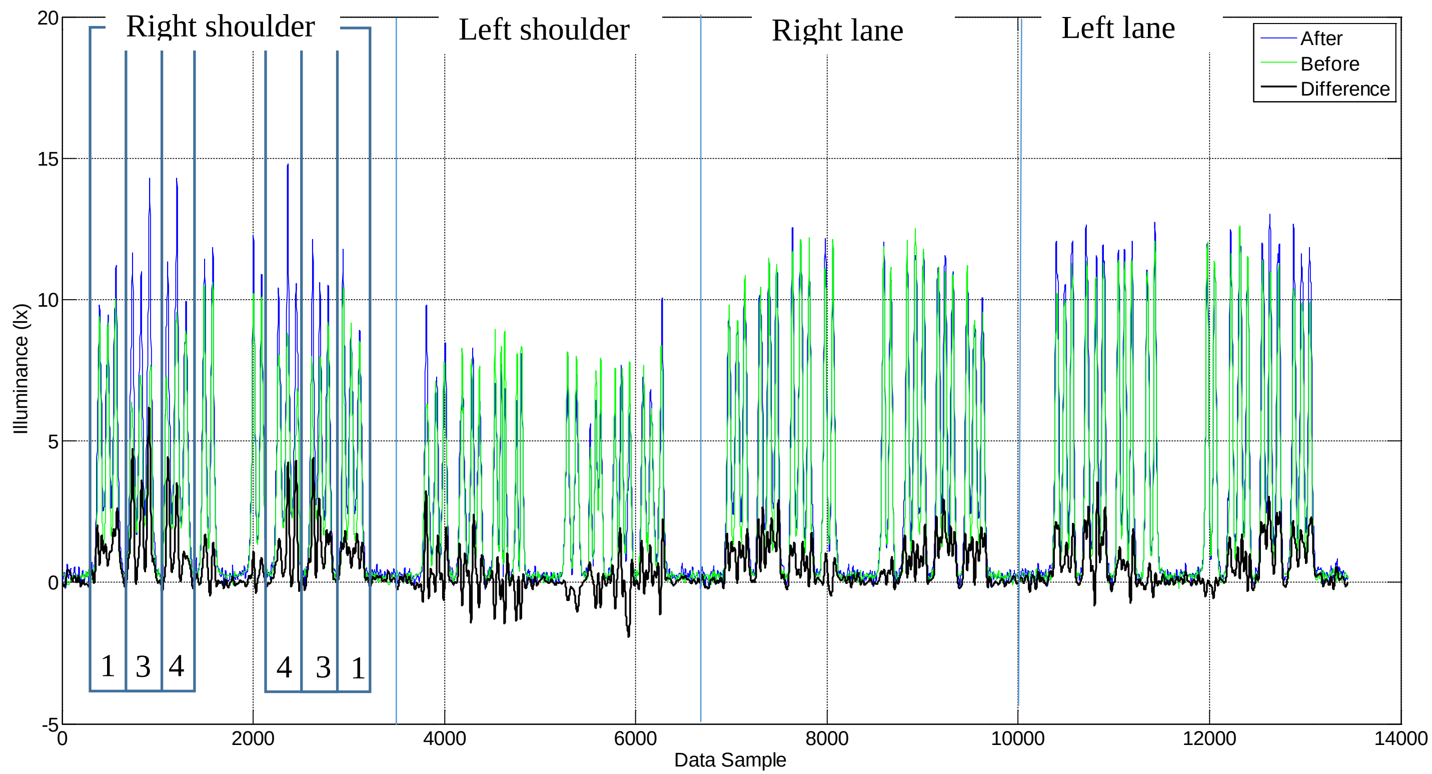


Figure 33**. Type A luminaire (3500K) data. From left to right, the groupings are right shoulder for two laps, traveling southeast, and then a return traveling northwest, left shoulder for two laps, right lane for two laps, and left lane for two laps. Each box shows a group of three luminaires, the after, and before measurement with the difference in black. The boxes are numbered with the cleaning method used. The biggest effect appears to be in the right shoulder (far shoulder).**

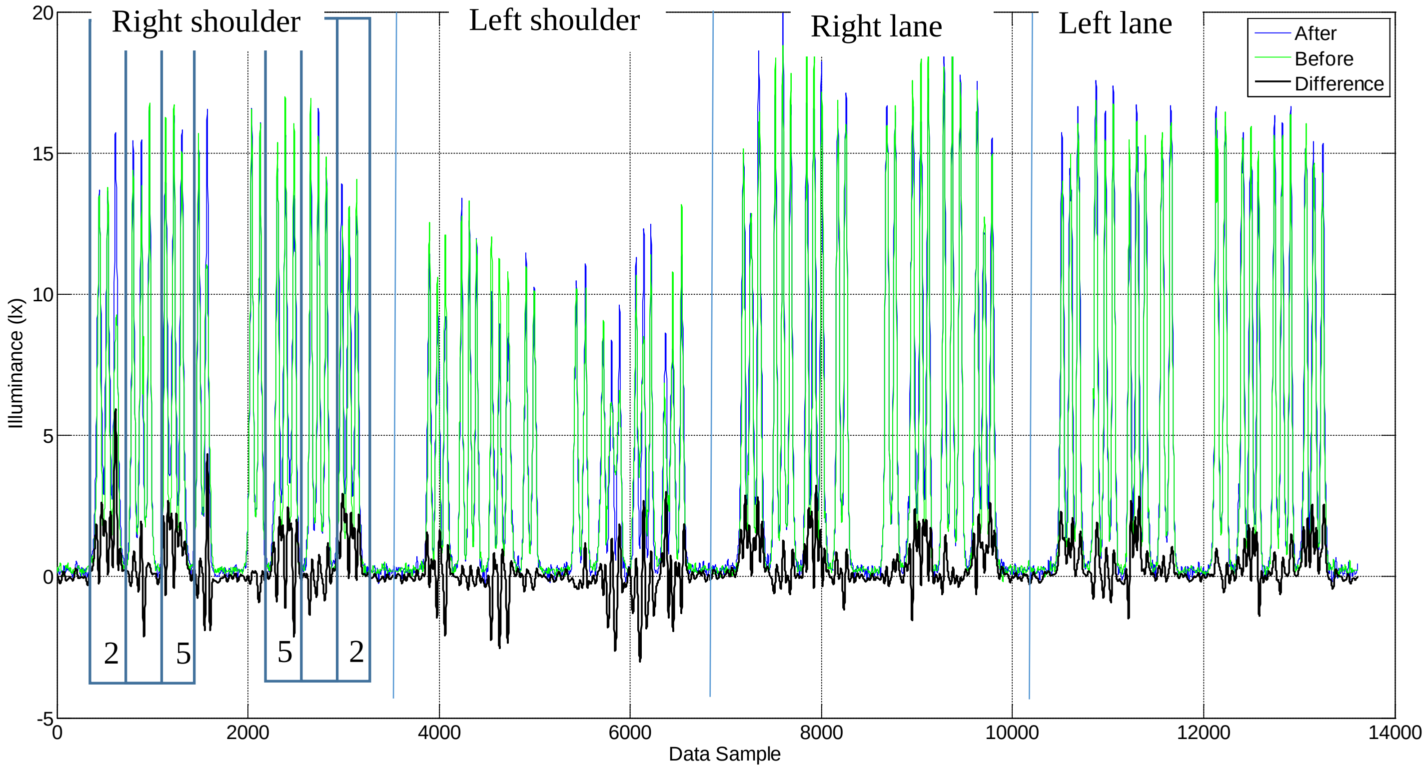


Figure 34. Type A luminaire (6000K) data. From left to right, the groupings are right shoulder for two laps, traveling southeast, and then a return traveling northwest, left shoulder for two laps, right lane for two laps, and left lane for two laps. Each box shows a group of three luminaires. The before and after horizontal illuminance measurements are shown with the difference in black. The boxes are numbered with the cleaning method used. Again the biggest effect appears to be in the right shoulder (far shoulder).

The measurements were performed within a week of each other and the background light was virtually identical between the two measurements, giving a difference measurement of very near zero in the dark areas between luminaires (Figure 33 and Figure 34).

These luminaire have been installed on the Virginia Smart Road for 6 years, and some have a dirt depreciation worse than 20% of average illuminance lost. It appears from the graphs (Figure 33 and Figure 34) that the IPA wipe was the most effective cleaning method. This makes some sense if it is assumed that unburned hydrocarbons and oil vapors are present with the dirt. The Smart Road has a 6% grade, which requires considerable throttle input on some vehicles. It is well known that all vehicles are configured to run rich for full throttle and acceleration, and therefore emit unburned hydrocarbons. In addition, the heavy trucks used on the Smart Road for research are older vehicles and likely emit unburned hydrocarbons any time they are operated.

ANALYSIS

The cleaning methods were assessed by selecting the data from the middle of the first peak of each set of three luminaires to the middle of the last peak. This allowed the study of one whole luminaire and half each of the other two luminaires. This method eliminated artificially low minimum readings where the luminaires were off between sections.

As shown in Figure 35, the average dirt depreciation recovery was largest for the 70% IPA cleaning method, while the pressure washing had the least effect on cleaning the luminaires. The data were averaged before dividing to get the dirt depreciation due to GPS errors preventing us from doing division at each data point. The three control sections (seven luminaires total) are shown to get an additional impression of the accuracy of the measurement methods. The errors in the data are calculated using the standard error:

$$Error = \sqrt{number\ of\ samples} \tag{1}$$

where the number of samples in this case equals the number of illuminance measurements.
In terms of dirt depreciation at the point of maximum horizontal illuminance, which was calculated by taking the peak values before and after cleaning, again 70% IPA resulted in the largest change in illuminance (Figure 36).

One thing should be noted about this analysis. The analysis assumed that each group of luminaires on the Virginia Smart Road had accumulated the same amount of dirt. This is a reasonable assumption because the luminaires have been installed on the road for identical time periods, and the studies performed on the Virginia Smart Road usually require vehicles to drive the entire length of the lit section. In addition, observation of the luminaires did not indicate there was any difference in dirt accumulation. However, there was no independent way to measure the dirt accumulation separate from the illuminance measurements before and after cleaning. It is assumed that any variance in the dirt was accounted for by utilizing more than one luminaire in each group.

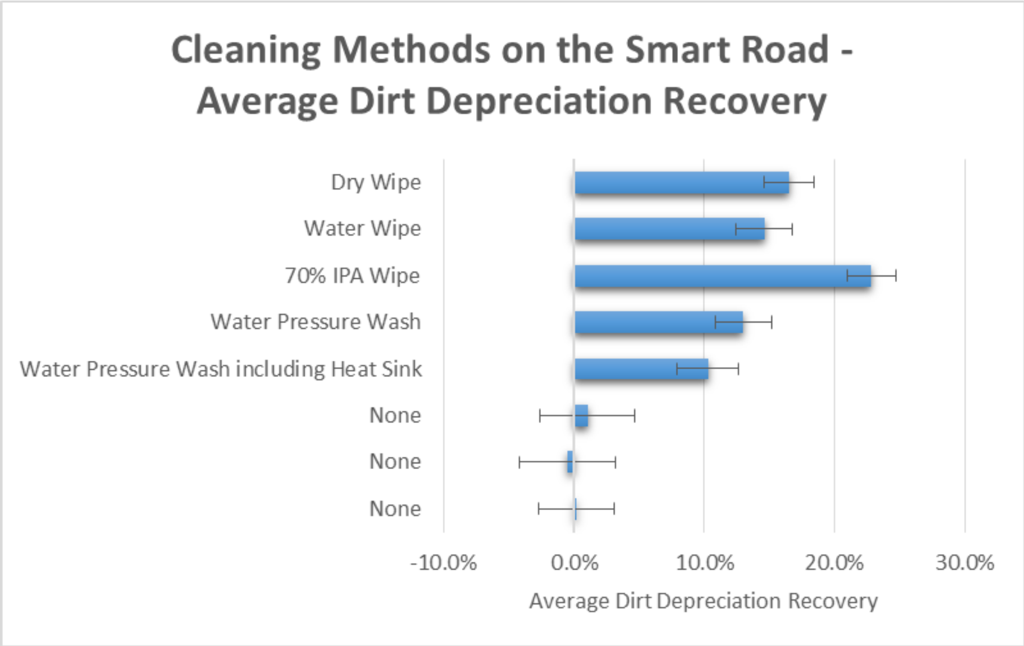


Figure 35. Cleaning method results in terms of average dirt depreciation recovery. The three controls were included as a measure of the measurement accuracy. The error bars indicate standard error, while the "None" bars indicate specific errors in the control measurements.

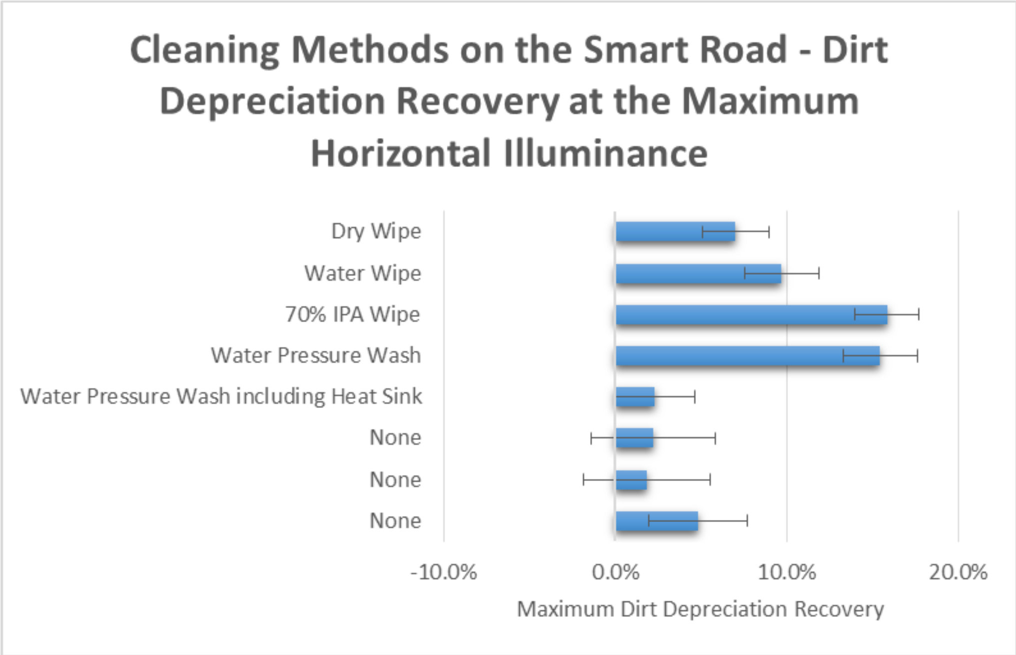


Figure 36. Cleaning method results in terms of dirt depreciation recovery at the point of maximum horizontal illuminance. The three controls were included as a measure of the measurement accuracy.

Uniformity was also calculated, using the average and minimum of each data set. Uniformity is defined as:

$$Uniformity = \frac{Average\ Illuminance}{Minimum\ Illuminance} \tag{2}$$

Since uniformity is a calculation based on two measurements, the error is calculated using the standard method for multiplication and division of measured quantities:

$$Error_{Uniformity} = Uniformity\ \times \sqrt{\left(\frac{Error}{Average}\right)^2 + \left(\frac{Error}{Minimum}\right)^2} \tag{3}$$

For these data, a negative percentage indicates a more uniform lighting pattern and a positive percentage indicates a less uniform light pattern. **Figure 37 shows that for these LED luminaires, which utilize individually molded acrylic optics and no external optic, the luminaires are more uniform when dirty and less uniform after cleaning.** Unfortunately, the ratio is sensitive to measurement error. As can be seen in Figure 37, the calculated standard error is larger than the measurements, so these data must be considered carefully.

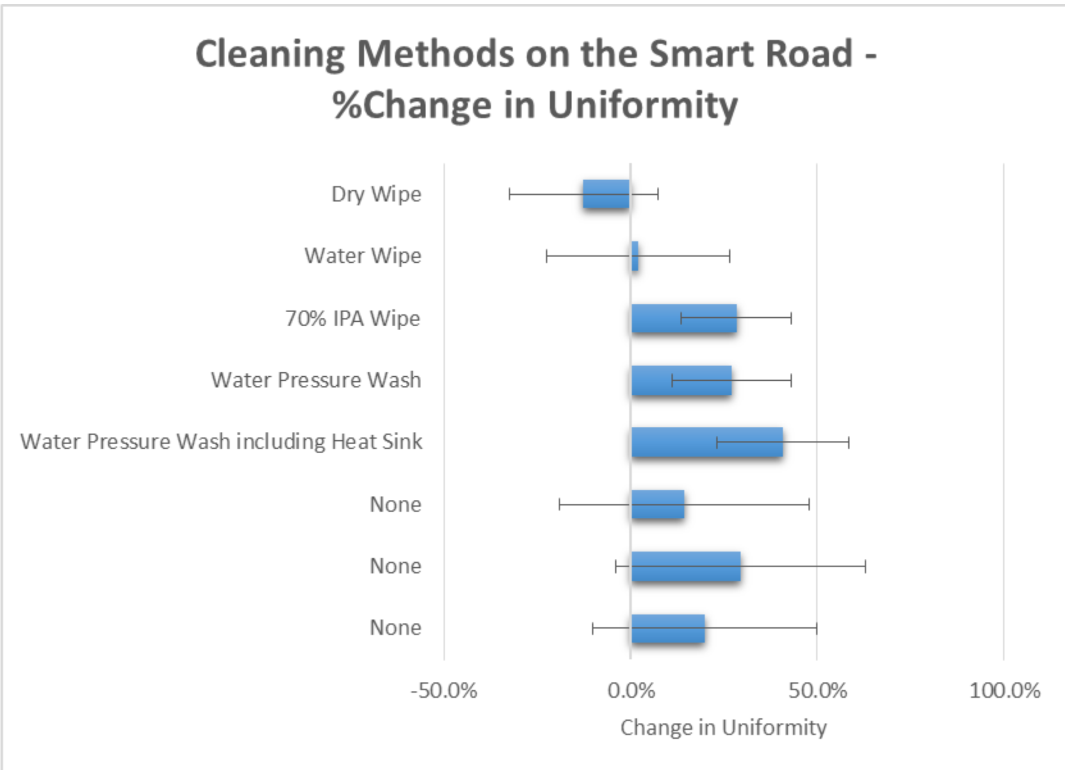


Figure 37. Uniformity change due to cleaning and error in the measurement.

Mild Detergent Cleaning Results

The data show that for these luminaires the detergent solution performed better at removing the dirt and restoring average illuminance (Figure 38). The maximum value of illuminance was higher for the 70% IPA wipe (Figure 39), but the resulting difference is within the error range, so it may not be statistically different.

Again, there is no way to know how much variation in dirt accumulation existed between the two sets of luminaires cleaned, or how this amount of dirt differed from the amount of dirt on the luminaires on the Virginia Smart Road. It is reasonable to assume that the Virginia Smart Road luminaires have very little if any salt content since it is not treated during winter weather, and experiments are not often run in icy and snowy conditions.

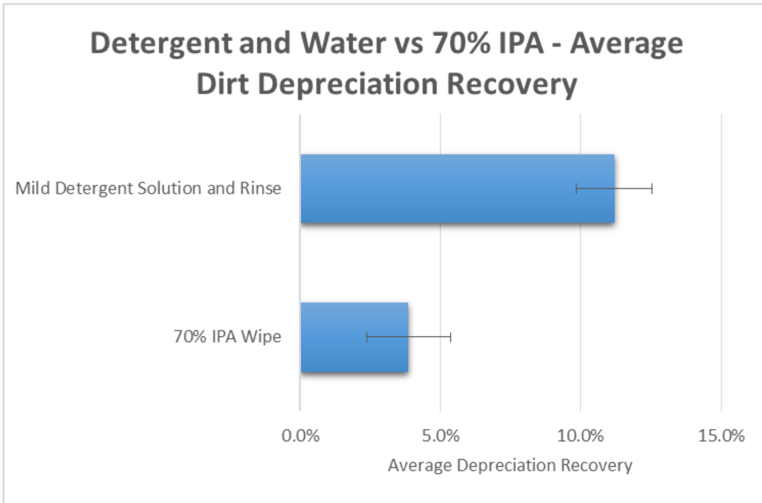


Figure 38. Cleaning method results in terms of average dirt depreciation recovery. These are results from the Hampton field study.

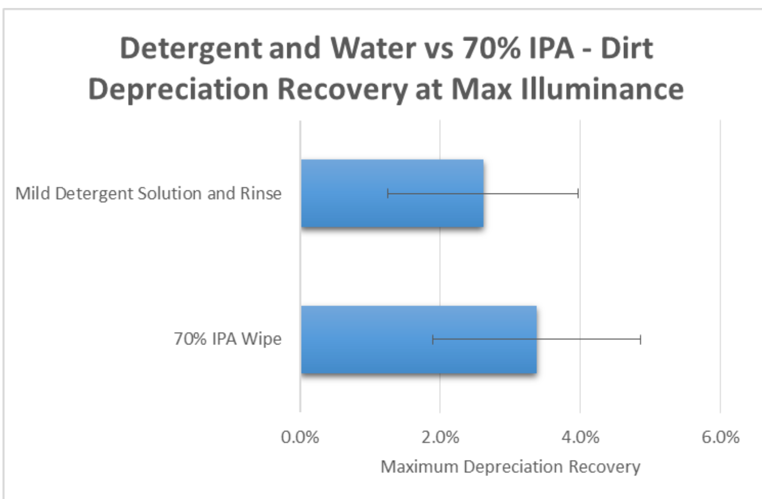


Figure 39. Cleaning method results in terms of maximum dirt depreciation recovery. These are results from the Hampton field study.

The uniformity change in Figure 40 is more negative for the detergent solution, indicating more uniform lighting after cleaning. For locations with high salt spray, cleaning with very mild detergent may be more effective than the alcohol wipe due to the polar nature of salt and the ability of water to remove the salt as well as hydrocarbon-based dirt.

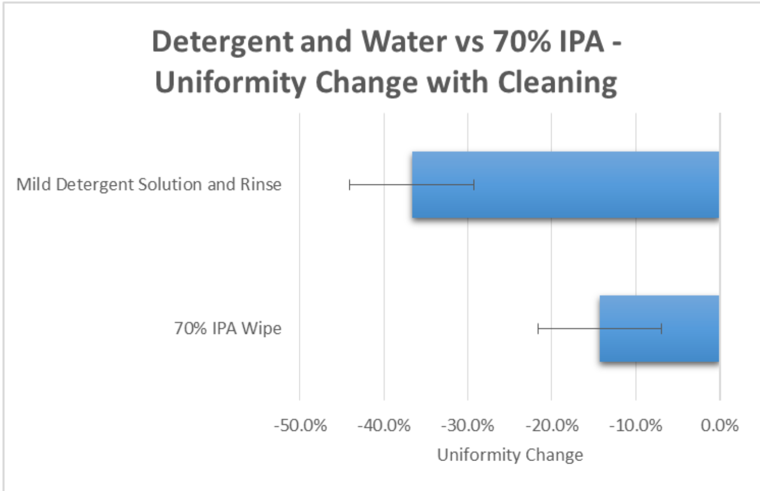


Figure 40. Cleaning method results in terms uniformity change. These are results from the Hampton field study.

PILOT STUDY CONCLUSIONS

Manufacturers recommend against cleaning with anything other than a dry rag or plain water. This pilot study concluded that those two methods are not effective at removing dirt accumulation. Cleaning of the acrylic and glass outer optics can be accomplished safely with either 70% IPA or a mild detergent solution created using a few drops of a mild dish washing detergent in a 250-ml container of water. The 70% IPA was most effective on the Virginia Smart Road, which does not have high traffic and does not get salt treatment for snow. The mild detergent solution was more effective than the 70% IPA at a coastal site where salt spray was more predominant than vehicle traffic. Pressure washing the luminaires with water was ineffective from the ground and only produced results from 1–2 ft away, which likely violates the IP rating of the luminaires.

RELATED WORK: LABORATORY STUDY

In a related project for VDOT (Ronald Gibbons 2015), a laboratory study was performed to gain a detailed understanding of how LDD varies across the light distribution of an LED luminaire. These data were mined, smoothed, and statistical summaries calculated for inclusion in the in situ analysis for this project.

METHODS

Equipment

Horizontal and vertical illuminance were measured using a Minolta® T-10 illuminance meter.

LED Luminaires Selected

Measurements were performed for five types of LED luminaires that were installed at the Woodbridge parking facility (Table 4). Photos of the luminaires are shown in Figure 41.

Table 4. Luminaires Tested for Luminaire Dirt Depreciation Distribution (Ronald Gibbons, 2015)

Design	Manufacturer	Type	Inside Optic	Outside Optic
HPS, 250 W	B	HPS	None	Flat glass
A	E	LED	Individual molded acrylic	None
B	F	LED	Molded acrylic	Flat glass
C	G	LED	Molded acrylic	Flat glass
D	H	LED	Individual molded acrylic	None
E	I	LED	Individual molded acrylic	Flat glass

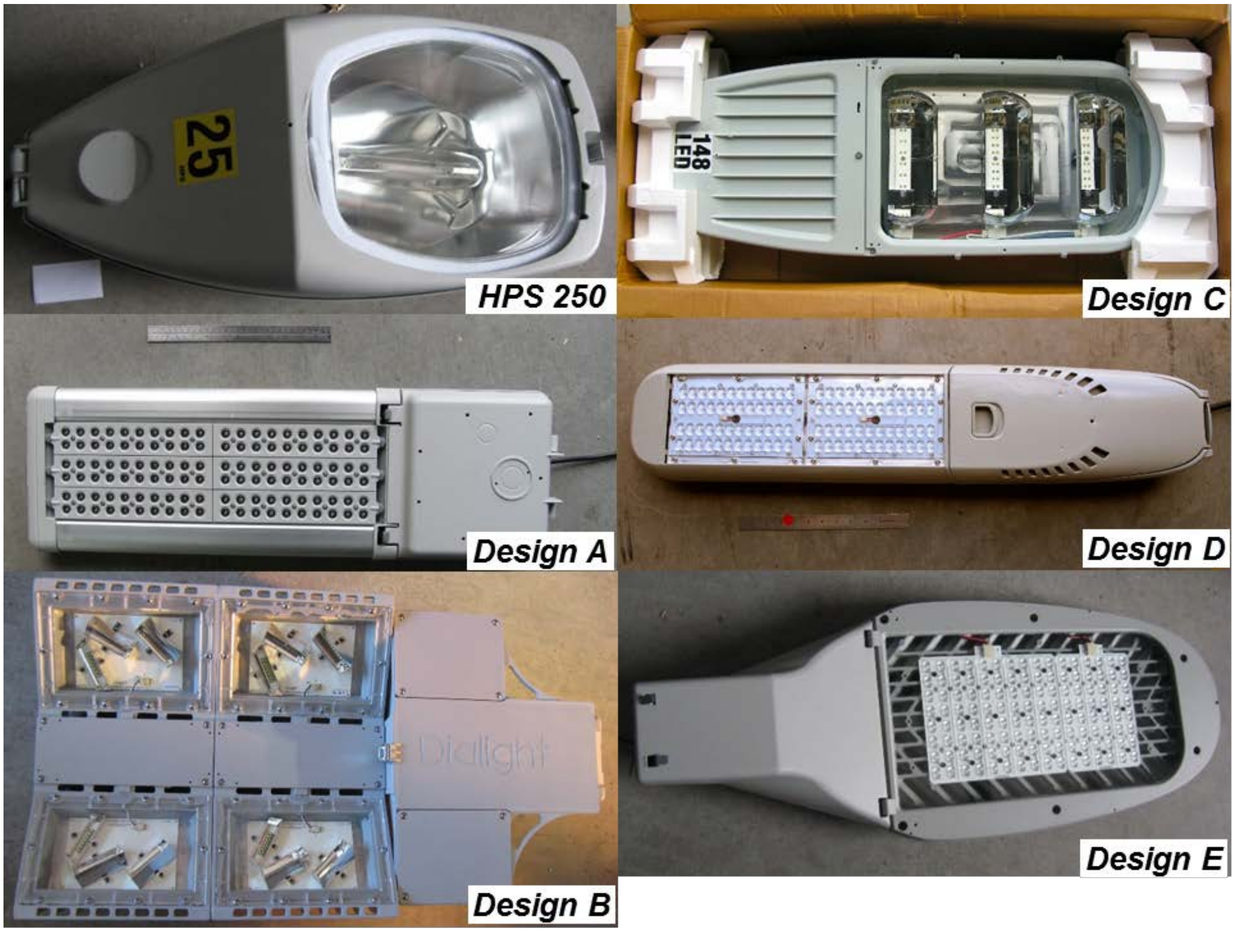


Figure 41. LED luminaires selected for LDD distribution testing (Ronald Gibbons (2015)).

Procedure

Each tested luminaire was mounted on the pole at the grid and care was taken to not disturb any accumulated dirt. A complete set of horizontal and vertical illuminance measurements were taken. All measurements were performed at night.

Horizontal illuminance was measured using a Minolta® T-10 illuminance meter, with the meter on the pavement, facing up, at the center of each cell in the 20 × 40 m grid, as shown in Figure 42. After measurements were taken, the LED luminaires were cleaned with the 70% IPA wipe method and the measurements were repeated.

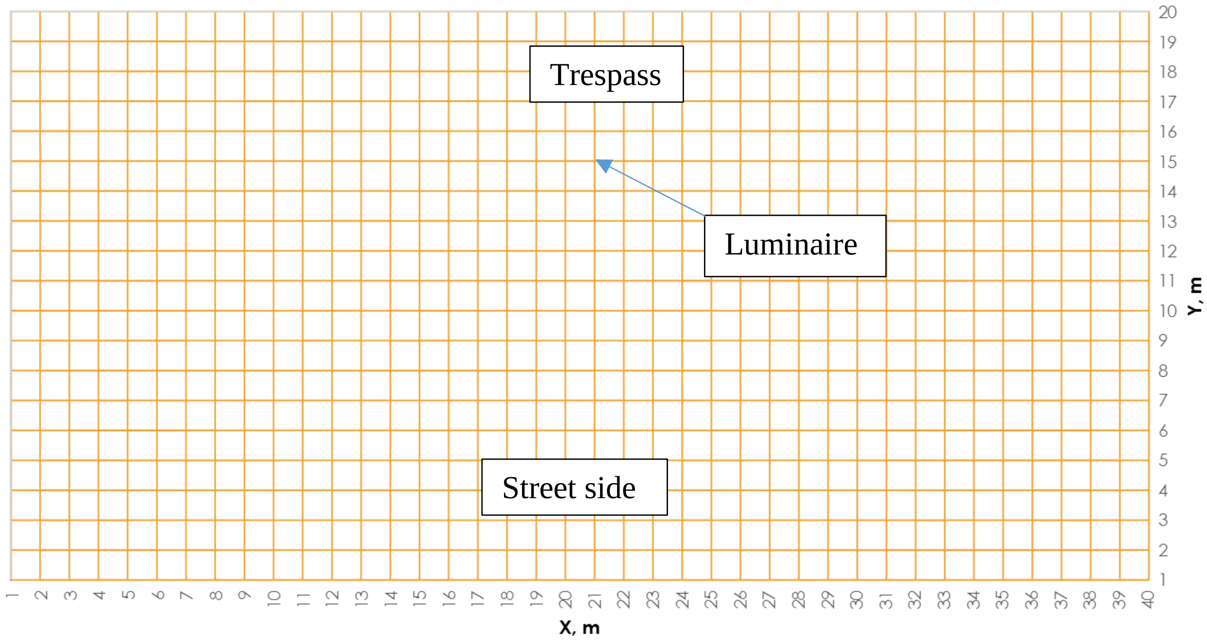


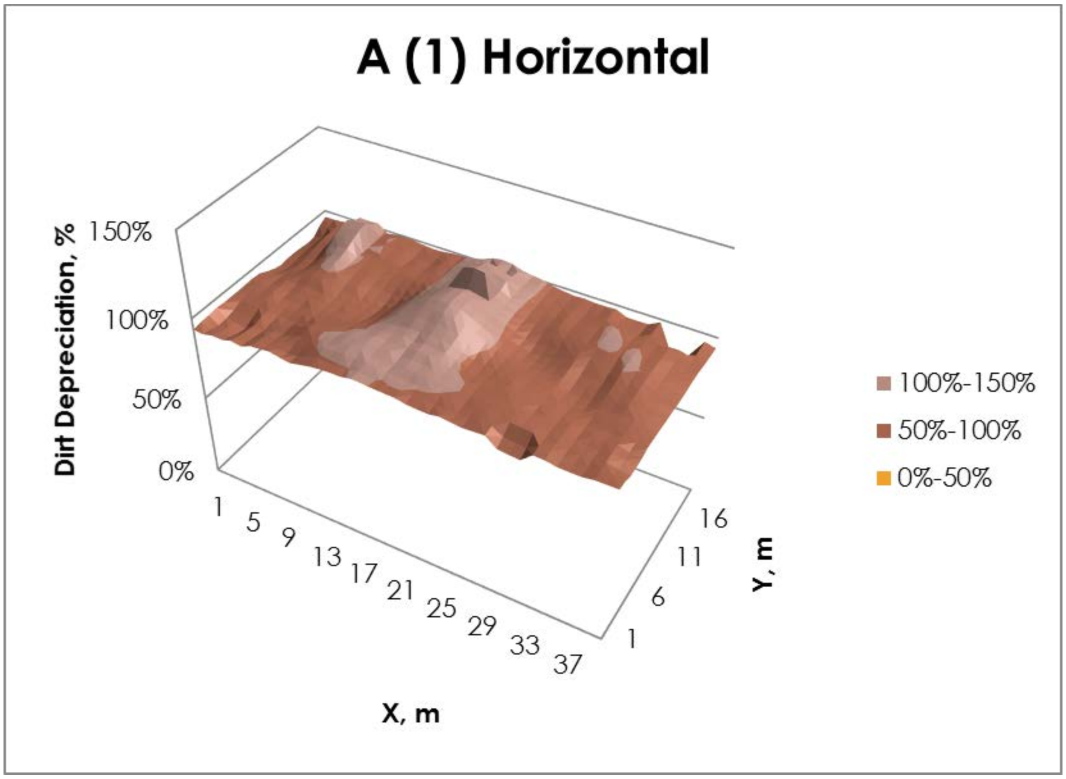
Figure 42. Horizontal and vertical illuminance measurement locations on the laboratory study measurement grid.

RESULTS

The research team compared the light distribution of each luminaire before and after cleaning the lenses. These data were then filtered to remove noise in the measurement. Figure 43 through Figure 47 illustrate the effect of dirt depreciation distribution on the horizontal illuminance for each luminaire.

Figure 43 shows the light loss (dirt depreciation) for the two Design A luminaires in terms of the percentage of horizontal illuminance, dirty versus clean at an oblique angle. These charts illustrate how dirt depreciation can skew the light pattern of luminaires. The location of the luminaire in Figure 43 through Figure 47 is at X = 20 m and Y = 15 m. The difference in light pattern is likely due to these two luminaires being mounted in different locations in the park and ride lot. The average illuminance lost due to dirt for the upper, A(1) luminaire was approximately 0.09 lx. The second luminaire appeared to gain an average of 0.022 lx. This may be due to insufficient cleaning or drift in the LED output with temperature.

More interesting is the pattern of light loss. For both luminaires the light was redistributed by the dirt accumulation to increase the lighting approximately 8 m from the centerline and 5 m in front of the luminaire while losing the most light 4 m directly in front of the luminaire. This is likely due to the dirt on the optics reflecting or scattering most of the light back into the luminaire as opposed to absorbing it. This results in a distribution with higher than 100% output in some locations for the dirty luminaire. This was found to be true for nearly all the LED luminaires. Also of note, the dirt accumulation in the park and ride resulted in different light patterns in each pair of identical luminaires. Therefore, the pattern changes may be difficult to predict a priori.



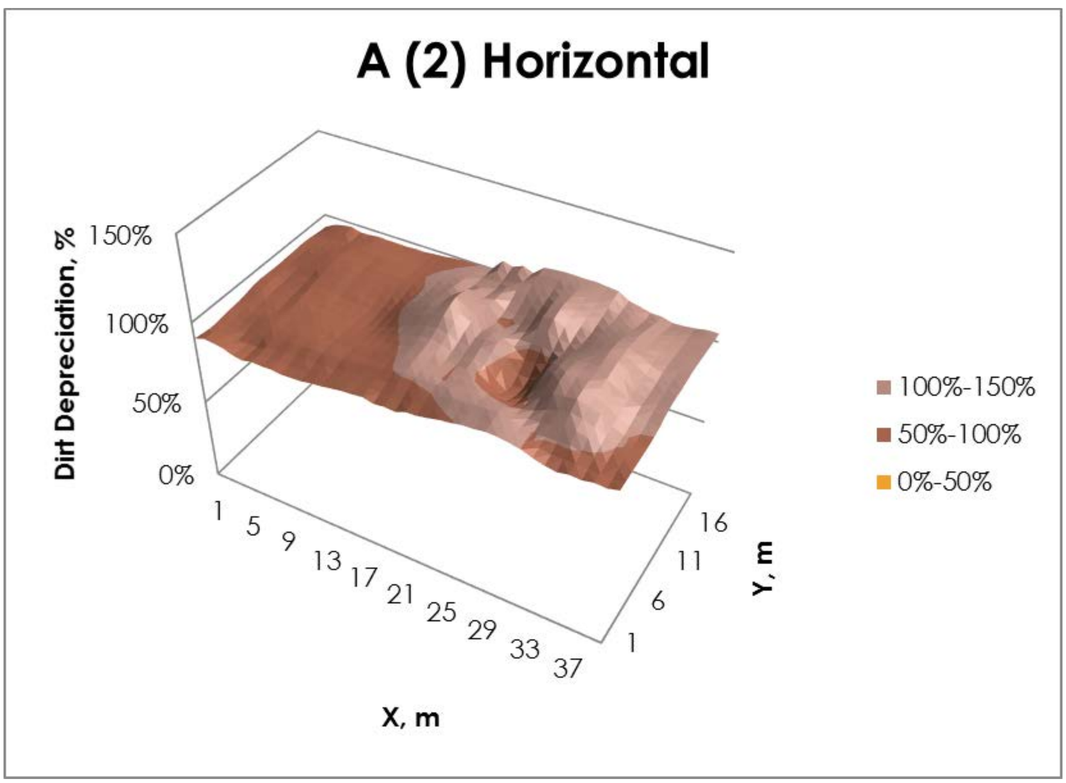


Figure 43. Horizontal dirt depreciation for two Design A luminaires with individual acrylic optical elements.

The Design B(1) luminaire had a 0.084 lx average illuminance loss due to dirt, and was fairly uniform in loss (Figure 44). This luminaire has flat glass optics over top of beam shaping optics.

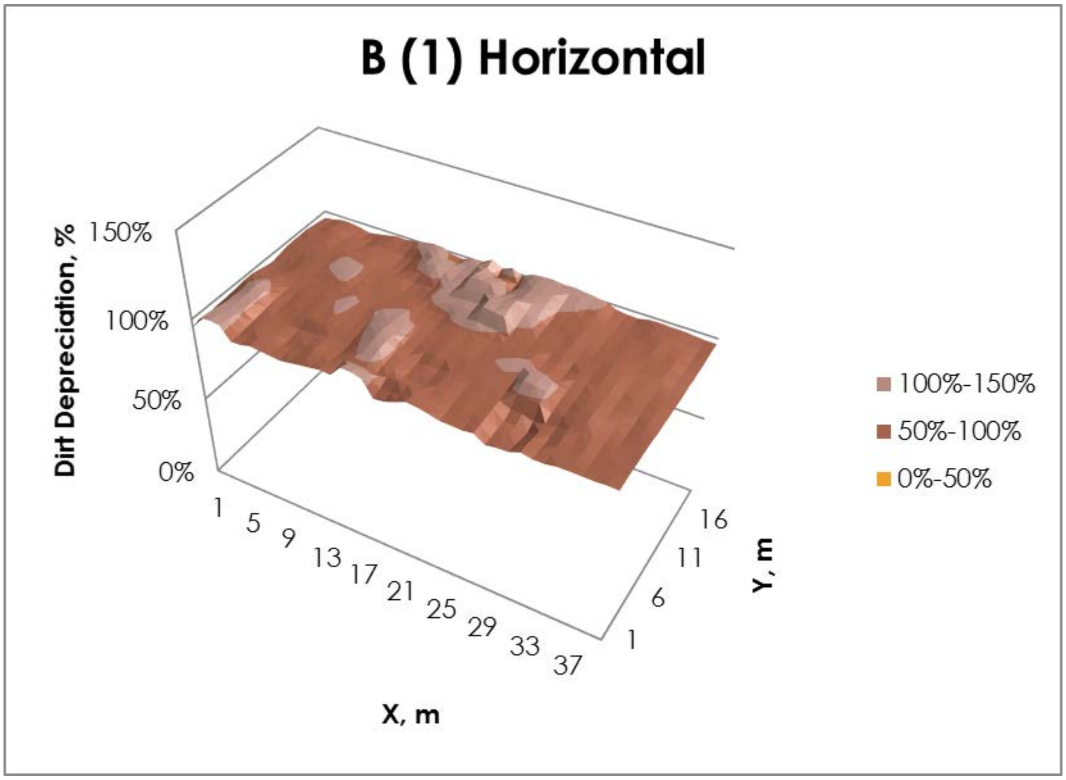


Figure 44. Design B(1) horizontal dirt depreciation in percentage of clean light output.

The Design C(2) luminaire had a higher average luminance loss of 0.5 lx (Figure 45) and higher peak loss. This luminaire has a flat glass optic over plastic beam shaping optics. The Design D(1) luminaire had an average illuminance loss of 0.088 lx (Figure 46). This luminaire utilizes individual plastic optics. The Design C(1) luminaire had no discernable dirt depreciation.

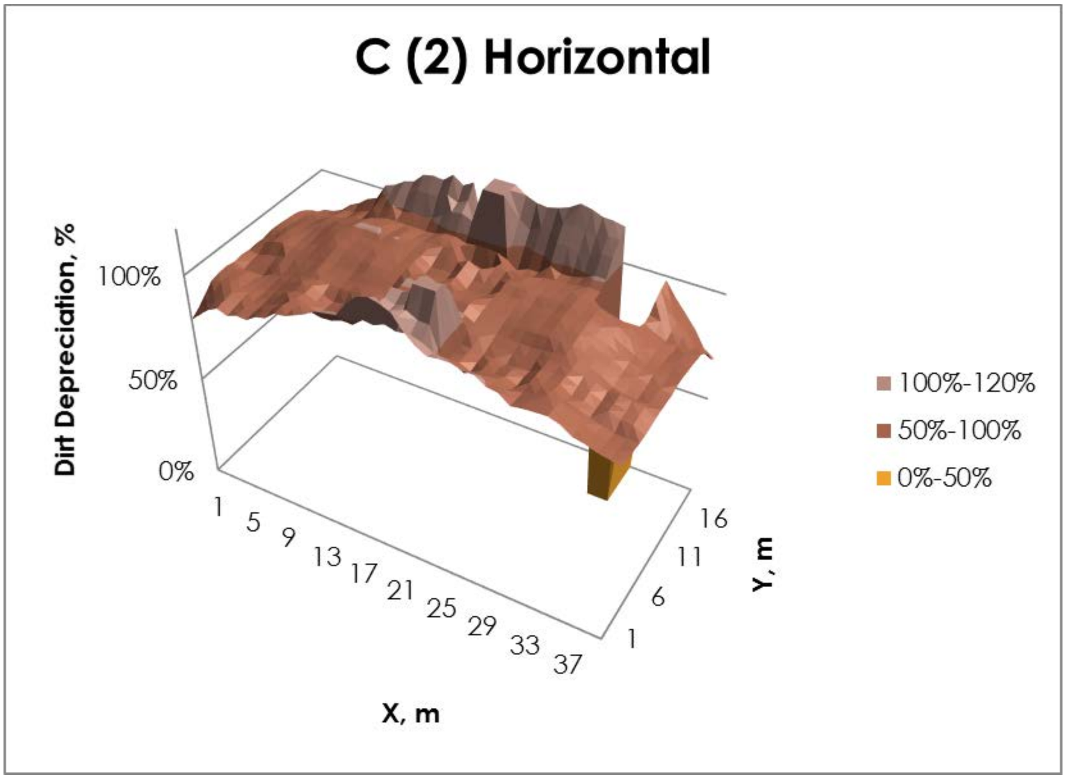


Figure 45. Design C(2) horizontal dirt depreciation in percentage of clean light output.

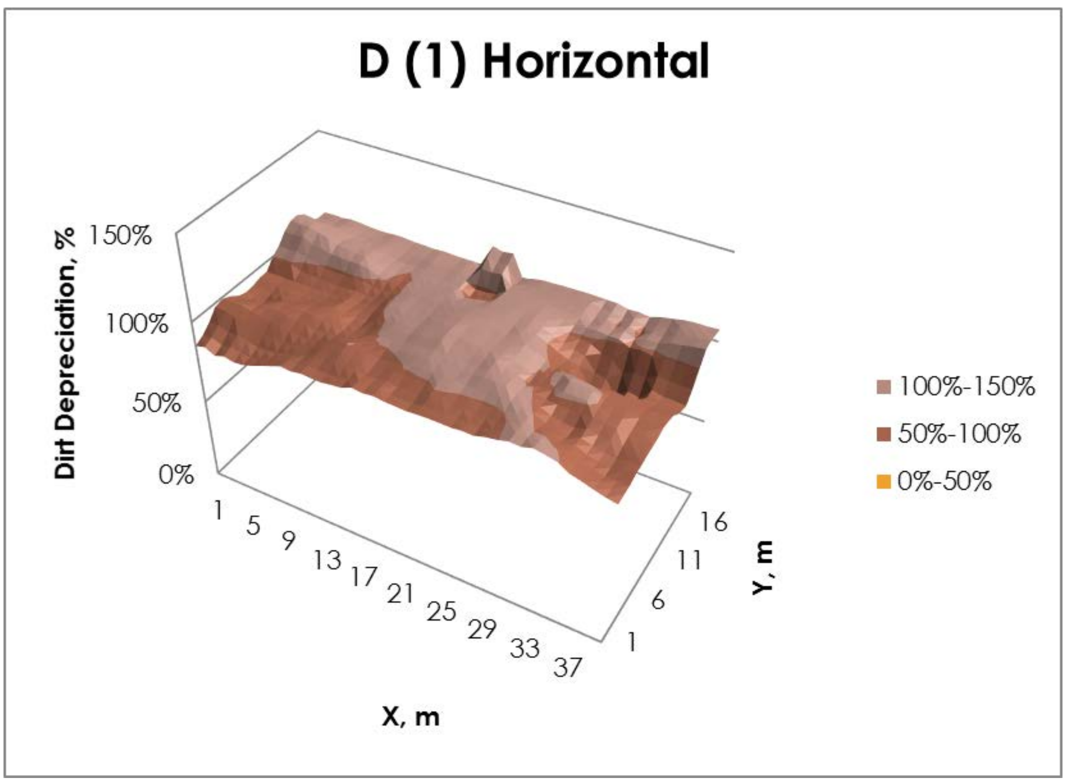


Figure 46. Design D(1) horizontal dirt depreciation in percentage of clean light output.

The Design E(1) luminaire had the second highest horizontal dirt depreciation of 0.37 lx with no discernable pattern (Figure 47). This luminaire utilizes a flat glass optic over individual plastic optics for each LED.

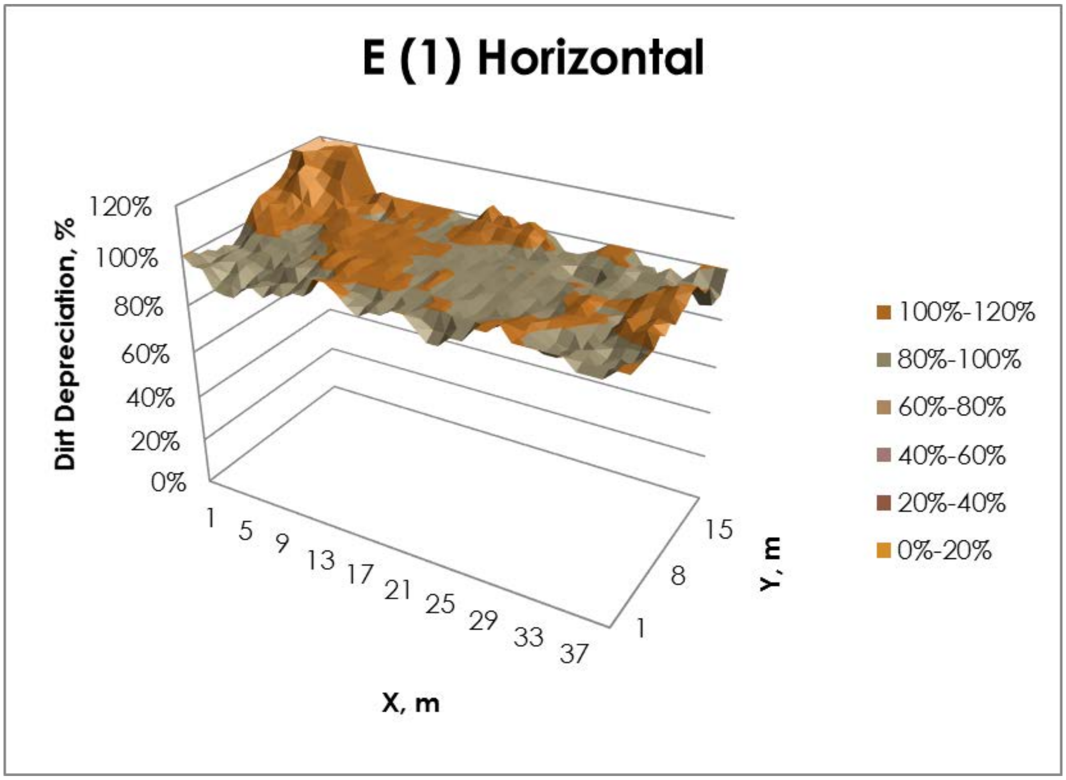


Figure 47. Design E(1) horizontal dirt depreciation in percentage of clean light output.

ANALYSIS

In the analysis for this report, the illuminance used for statistics was measured from 12 m in front of the luminaire to 4 m behind the luminaire. This allowed the elimination of some outliers from the averages and minimums. The average dirt depreciation versus optic type is shown in Figure 48. As opposed to the graphs for the most effective cleaning method, which were presented in terms of recovery, the following charts are presented in terms of dirt depreciation.

Figure 48 shows how the different combinations of inner and outer optics affect the dirt depreciation in this parking lot. Again, the HPS luminaire is included for comparison. One Design D luminaire appeared to get brighter after cleaning. Due to weather, some of the clean and dirty illuminance measurements were separated by up to a week; therefore something else changed, most likely temperature. This luminaire was not included in the final analysis.

The dirt depreciation for each luminaire at the position of maximum illuminance (usually nearly directly under the luminaire), as shown in Figure 49, does not correlate well with the average dirt depreciation shown in Figure 48. This is, again, due to changes in the pattern of lighting produced.

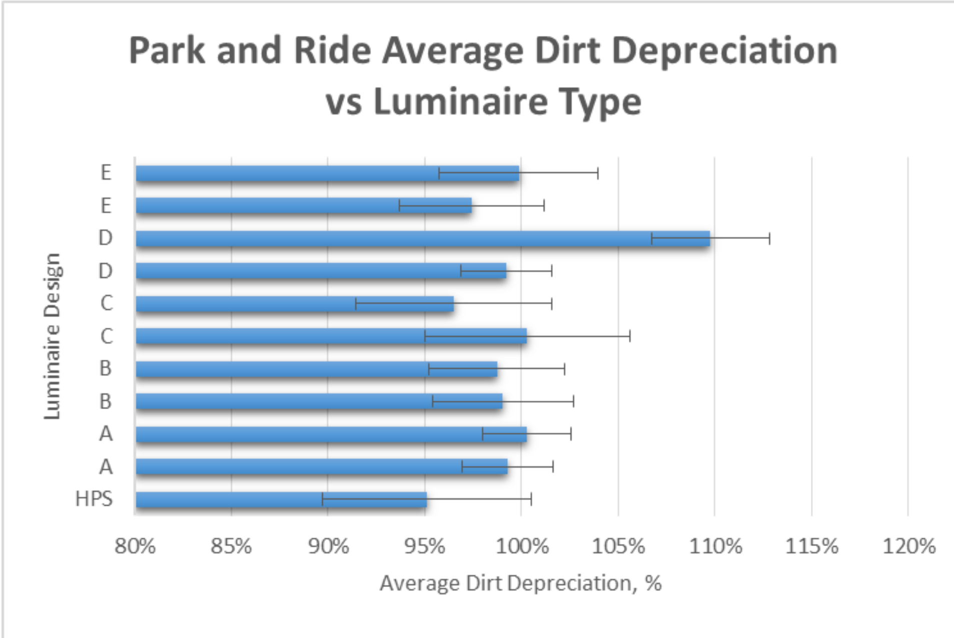


Figure 48. Average dirt depreciation vs. types of optics. HPS light for comparison.

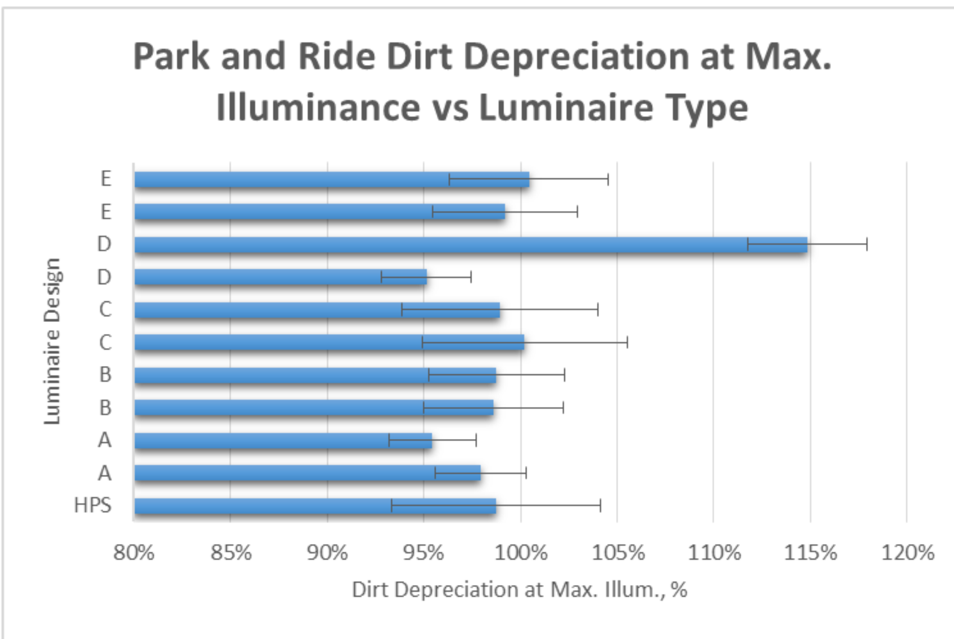


Figure 49. Maximum dirt depreciation vs. type of optics. An HPS light for comparison.

Figure 50 shows the change in uniformity, which is the ratio of the dirty uniformity to the clean uniformity. As can be seen, in most cases the uniformity ratio decreased with increasing dirt, indicating that the pattern was becoming more uniform. There are a few exceptions: one Design C and one Design A luminaire had worsening uniformity. These two luminaires both had flat glass outer optics. However, the error, calculated again with the standard method for division of measurements (Eq. 3) and shown as error bars in the graph, is considerably larger than the differences, so again this data should be considered carefully.

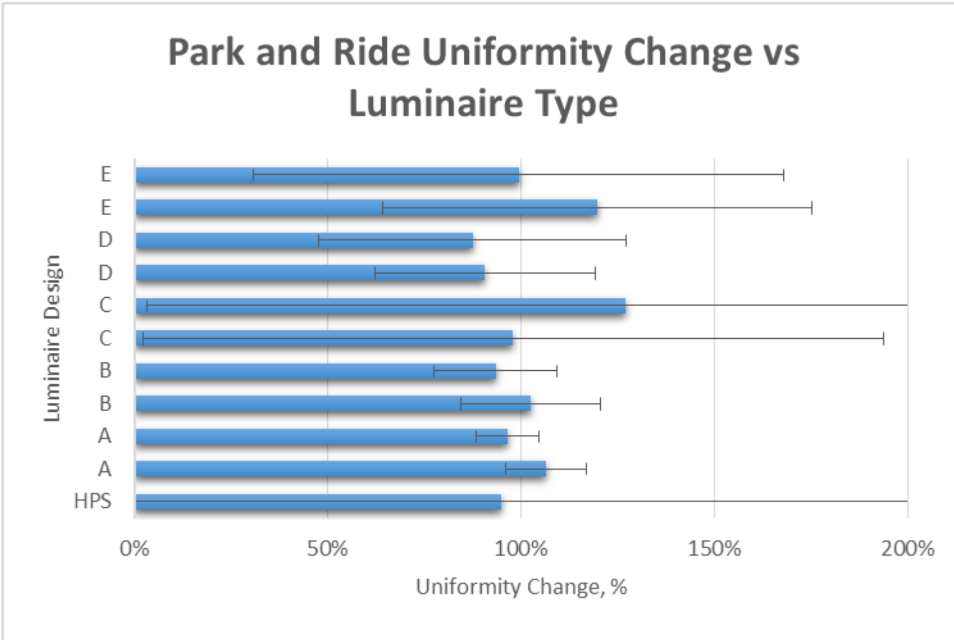


Figure 50. Uniformity change vs. type of optics. An HPS light for comparison.

SUMMARY

Careful measurement of the illuminance of luminaires in an (outdoor) laboratory resulted in measurable differences in average illuminance and uniformity similar to that found during the pilot study. However, there were some differences from one luminaire to the other even when they were of the same design. Further analysis of these data is performed in the overall analysis in the next section.

IN SITU STUDY

The purpose of the in situ study was to study the dirt depreciation on LED luminaires exposed to real-world traffic and environments. Sites were selected based on LED optics, installation age, traffic volume, and environment.

METHODS

The data collection for each field location was identical. First the illuminance of the area in the vicinity of the dirty luminaires was measured with the RLMMS. Then the team cleaned a number of luminaires, leaving some additional number dirty for control. The team remeasured the illuminance of the area with the RLMMS on the same vehicle. The cleaning protocol used was selected during the pilot study and consisted of 70% IPA with microfiber cloths.

The data were converted to dirt depreciation by taking the dirty illuminance and dividing by the clean illuminance at each location and subtracting from 1. The GPS coordinates were linearly interpolated so that both the dirty and clean data are at the same locations.

Table 5 shows the in situ sampled LED luminaires. The table details the number of luminaires sampled at each location and the age of each installation. Table 5 shows the type of luminaire sampled by LED optic (inner or external when there was no luminaire optic), luminaire optic (external), and identifies different designs with letter designations. Manufacturers are also identified by a letter designation. Due to resource limitations, the team was not able to develop a full factorial data collection experiment where all optical types were sampled at different ages and in different environments. Instead, the team selected locations with different environments for a single type of luminaire, as well as locations with different types of luminaire optics to develop a sparse matrix of data to analyze.

The 51 LED luminaires used in the analysis were measured, cleaned, and measured again. This included nine LED luminaires mined from the related study. For the in situ measurements, the data analyzed stretched from directly under one luminaire to directly under another luminaire, with as many whole luminaires included as possible to create an RP-8-like measurement grid. This minimized the impact of uncleaned lights on the measurements.

Installation ages ranged from 3 to 7 years, and the average annual traffic data (AATD) ranged from approximately 20 for the Virginia Smart Road (estimated) to 280,000 for the I-35W bridge (both lanes).

As can be seen in Table 5, the only optical material missing was individually molded polycarbonate, which based on the literature review comprises only 5% of the available LED roadway lighting luminaires (Table 1). Therefore the project data collected applies to approximately 95% of the roadway luminaire optic types.

The in situ study included a small study of cleaning methods at the Hampton, Virginia, location. There, one set of luminaires was cleaned with 70% IPA, one set cleaned by a mild detergent solution with a water rinse, and a third set left dirty for control. The results of the cleaning method comparison are reported in the pilot study section.

Table 5. Dirty LED Data Collection Matrix

Number of Luminaires	Design	Manufacturer	LED Optics	Luminaire Optics	Installation Age, yrs.	Location	Cleaning Method	Measurement Method	AADT
5	A	E	Individual Molded Acrylic	None	3	Hampton	70% IPA Wipe	RLMMS	86000
5	A	E	Individual Molded Acrylic	None	3	Hampton	Mild Detergent Solution and Rinse	RLMMS	86000
10	A	E	Individual Molded Acrylic	None	7	I - 35W Bridge	70% IPA Wipe	RLMMS	280000
2	A	E	Individual Molded Acrylic	None	6	VA Smart Road	70% IPA Wipe	RLMMS	20
1	A	E	Individual Molded Acrylic	None	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	A	E	Individual Molded Acrylic	None	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	B	F	Molded Acrylic	Flat Glass	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	B	F	Molded Acrylic	Flat Glass	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	C	G	Molded Acrylic	Flat Glass	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	C	G	Molded Acrylic	Flat Glass	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	D	H	Individual Molded Acrylic	None	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	E	I	Individual Molded Acrylic	Flat Glass	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
1	E	I	Individual Molded Acrylic	Flat Glass	3	Park and Ride	70% IPA Wipe	T-10a Grid	553
9	F	A	Molded Glass	White Reflector	4	61	70% IPA Wipe	RLMMS	20100
3	F	A	Molded Glass	White Reflector	5	77	70% IPA Wipe	RLMMS	69953
2	G	B	Individual Molded Acrylic	None	5	77	70% IPA Wipe	RLMMS	69953
3	J	C	Molded Acrylic	Flat Glass	5	77	70% IPA Wipe	RLMMS	69953
1	K	D	Large Molded Individual Acrylic	None	5	77	70% IPA Wipe	RLMMS	69953
2	L	J	Individual Molded Acrylic	Flat Glass	5	77	70% IPA Wipe	RLMMS	69953
1	HPS	B	None	Flat Glass	3	Park and Ride	70% IPA Wipe	T-10a Grid	553

RESULTS

Unfortunately, the data collection system had a GPS failure during the data collection at the Woodbridge, Virginia, site that was not discovered until after the luminaires had been cleaned. The team therefore included the data from the related project in the overall analysis. The data collection system worked flawlessly for the remainder of the in situ data collection.

Charleston, West Virginia, Observations

One of the interesting observations of the Design F luminaire was that many spiders had taken up residence in these luminaires (Figure 51, left) and had built webs across the concave bottom of the luminaire in order to capture food. Presumably, they were able to do this because of the concave nature of the luminaire and due to the temperature of LED luminaire being lower than typical HPS or metal halide luminaires. Proximity to the Kanawha River may have had an influence as there were no spiders observed in the four Design F luminaires installed on I-77.

Other observations included failure of half of one of the Design F luminaires installed on I-77, and failure of one LED out of 126 in one of the two Design G luminaires cleaned (Figure 52).

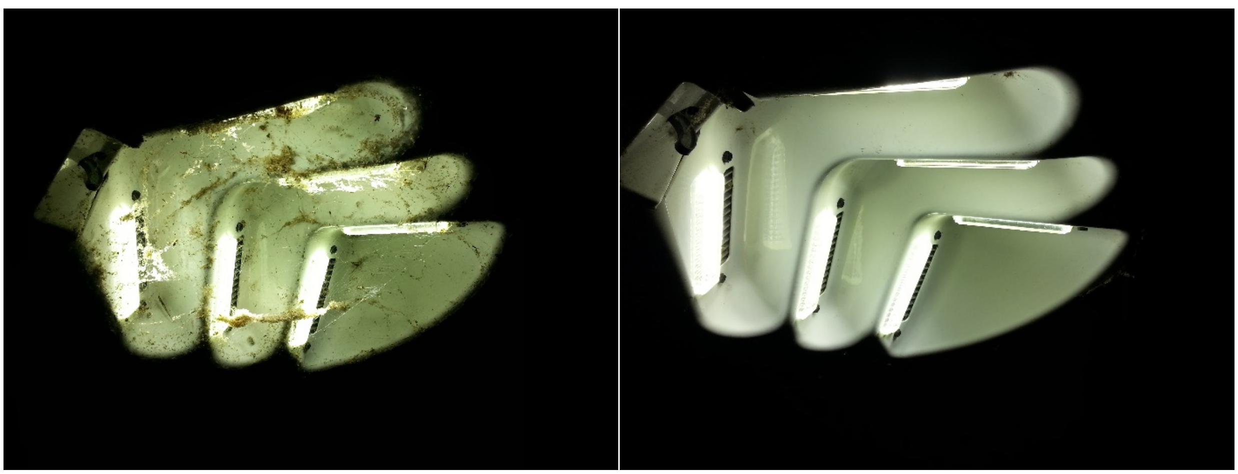


Figure 51. Design F, large molded glass optics and white concave reflector, dirty (left), clean (right)

Figure 52. Design G showing failure of one LED unit out of 126.

Since these luminaires needed to be cleaned at night due to lane closure restrictions, it is difficult to see a difference in some of the before and after photos (Figure 53).

Figure 53. Design G, individual molded plastic optics, dirty (left), clean (right). The photographs do not capture the difference between the dirty and clean very well.

In Figure 53 the dirt on the flat glass luminaire optic is clearly evident after cleaning.

Figure 54. Design J, flat glass over large molded optics, dirty (left), clean (right).

In Figure 54, the before and after photographs illustrate a challenge associated with cleaning a luminaire. The cleaning method left a film on the glass of the lower right quadrant of the lighting that was not noticed at the time of cleaning. The other three quadrants look cleaner in the after photograph.

Figure 55. Design K, flat glass optics over individually molded optics, dirty (left), clean (right).

The Design L luminaires, with large individual molded optics, seemed to have accumulated significantly more dirt than the other luminaires on I-77 (Figure 56).

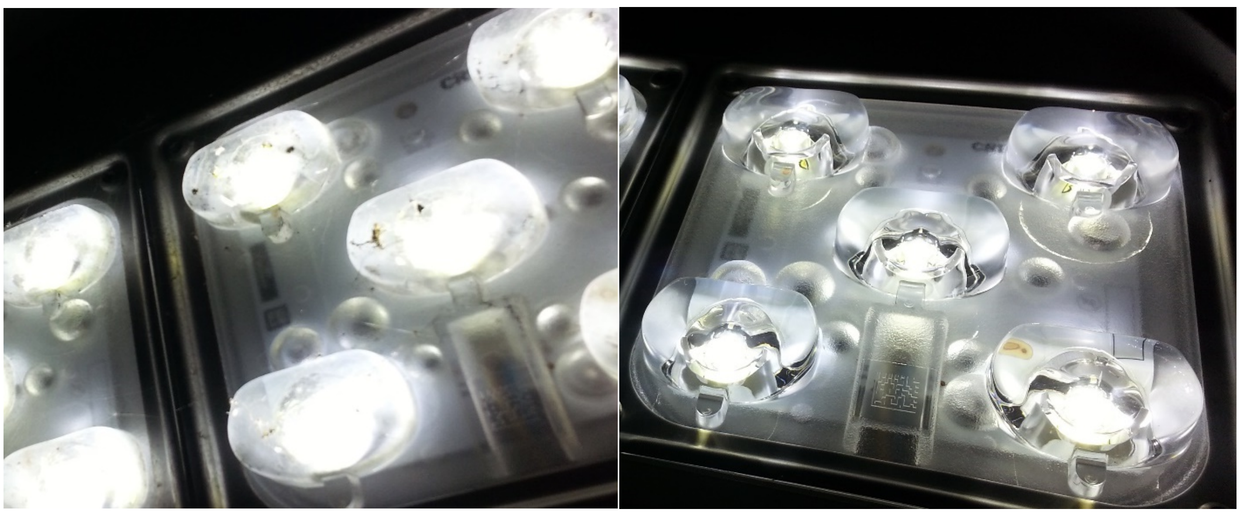


Figure 56: Design L, large individual molded plastic optics: dirty (left) and clean (right).

Hampton Observations

There was no observable difference between the before and after cleaning photographs as shown in Figure 57.

Figure 57. Before and after cleaning pictures. There is no visual difference.

As can be seen in Figure 58, there are many forms of dirt that can affect luminaire performance.

Figure 58. Bird perched on a luminaire heat sink.

Minnesota Observations

It is difficult to see the difference between the dirty and clean luminaire optics, especially for individually molded optics like the ones used on the I-35W bridge. However, as can be seen in Figure 59, the dirt that has accumulated on the LED modules can be clearly seen and is removed by the cleaning procedure. However, the dirt accumulation on the optics is not as obvious. These luminaires are from the same manufacturer as the luminaires installed on the Virginia Smart Road and are very similar in design.

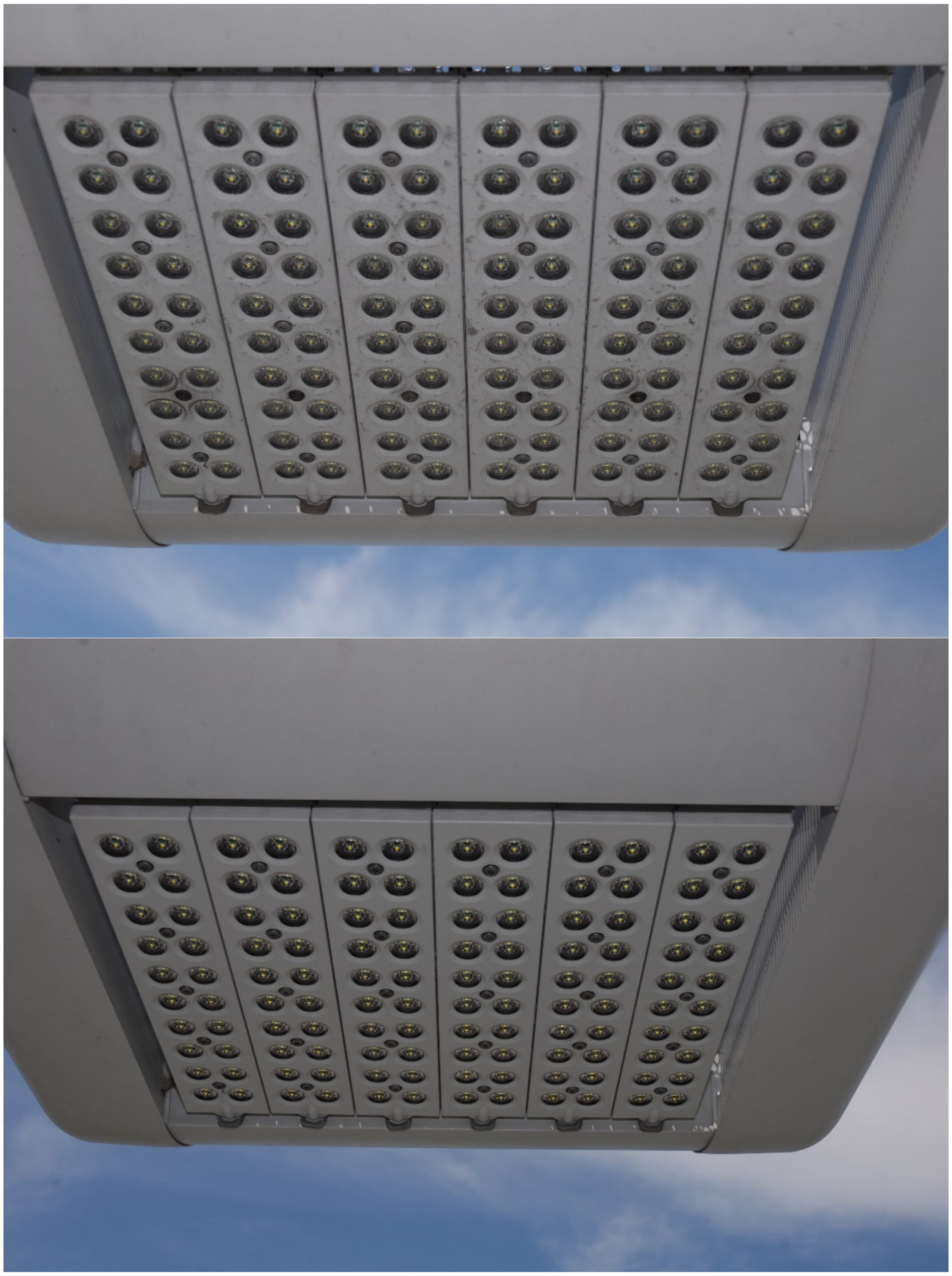


Figure 59. I-35W luminaire before cleaning (top) and after (bottom). The dirt is difficult to see on the optics.

Example raw data from the I-35W bridge in Minneapolis, Minnesota, are shown in Figure 60. This chart shows the after-cleaning horizontal illuminance data collected using the RLMMS system. The colors represent illuminance in lux, where blue is 0 and red is 25. The light patterns of the luminaires are clearly visible. The GPS positions of luminaires are marked with black dots in-between the lanes.

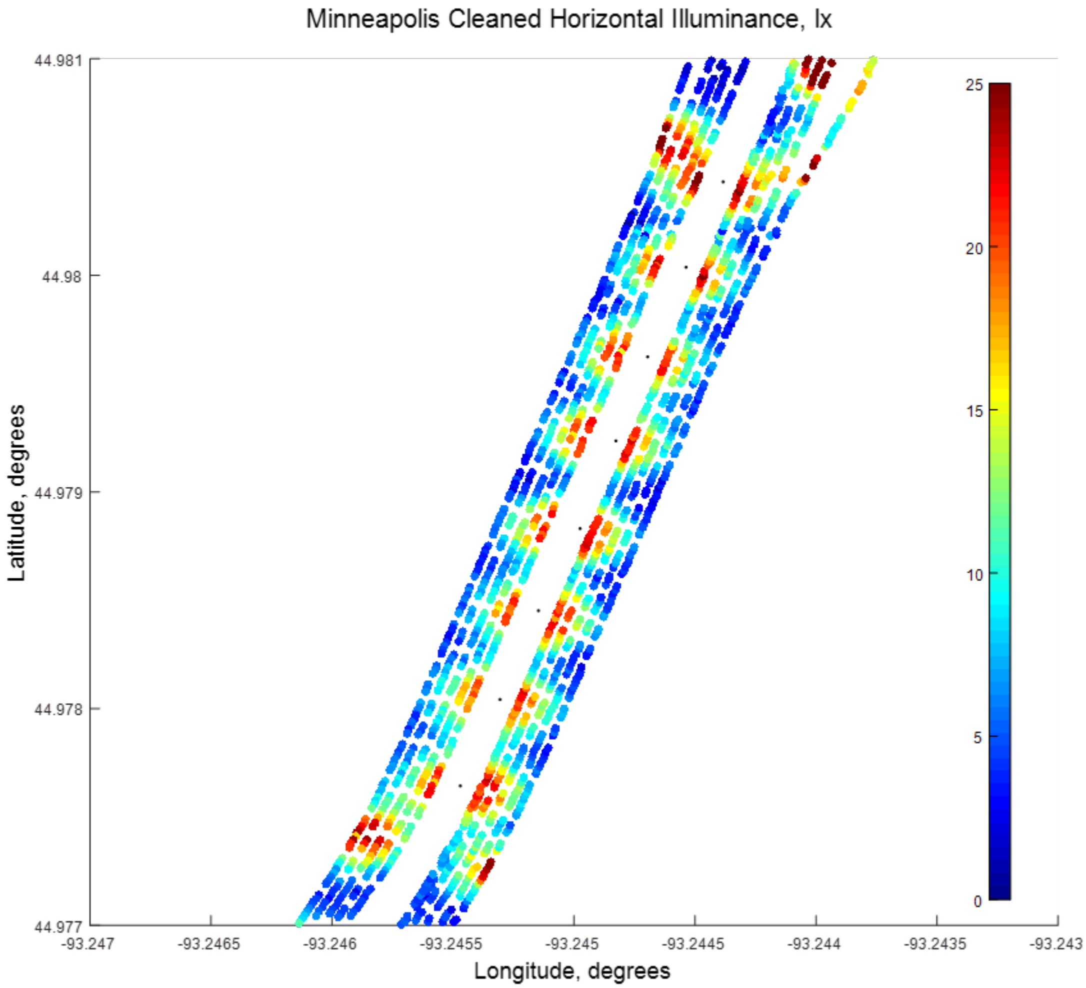


Figure 60. Minneapolis I-35W cleaned horizontal illuminance preliminary data.

Figure 61 shows the dirt depreciation in each lane of the I-35W bridge after cleaning all but four of the luminaires mounted in between the northbound and southbound lanes. Here the color scale is from 50% to 150% dirt depreciation; in other words, 50% to 150% of the cleaned horizontal illuminance. As in the last graph, black dots are used to mark the GPS coordinates of the luminaires.

This range was selected to highlight changes in the output of the lighting between dirty and clean. In this case, 100% is green. Any color on the blue side of the spectrum is lower output when dirty and any color on the red side of the spectrum is higher than 100% output at that location when dirty. As can be seen, the highest depreciation is in-between the luminaires, while less depreciation occurs directly under the luminaire in the southbound lanes. The pattern for the northbound lanes is skewed northward some.

The team left four luminaires uncleaned (circled in Figure 61). The dirt depreciation in this area should be near 100%, so the variation in this vicinity must be due to various errors in the measurements. The dirt depreciation calculation is very sensitive to error and noise when the measurement is near zero. The measurements on the unlit sections of roadway (not shown) were compared, with approximately 1 lx of error, indicating that the errors were not changing due to the background lighting.

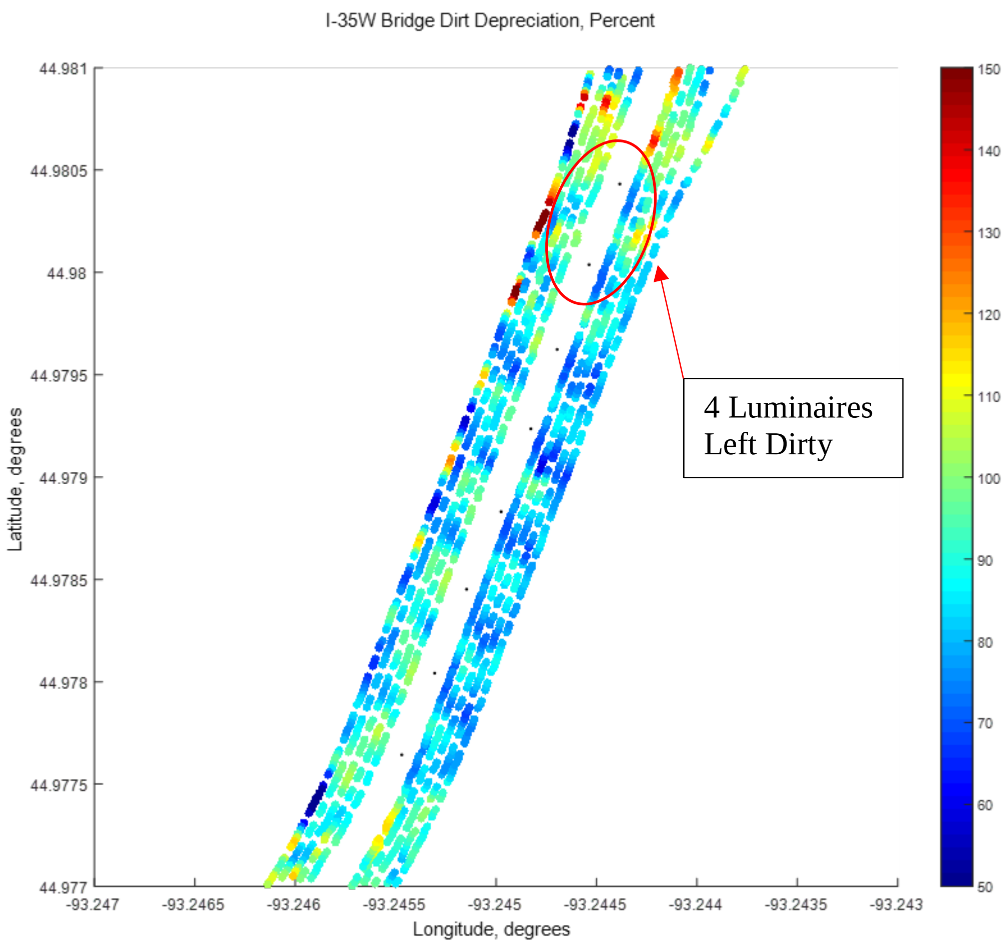


Figure 61. I-35W bridge dirt depreciation results in percentage of original illuminance value.

As illustrated, the dirt depreciation affects not only the overall light output of the luminaire, but also the pattern of light distribution. The dirt depreciation is highest near the periphery of the light distribution and not uniform. This was also seen in the data collected on the Virginia Smart Road, and is seen in all of the in situ data sets.

Table 6 contains all of the summary data for every sampled LED luminaire and the one sampled HPS luminaire. The LED luminaires were all cleaned with 70% IPA except for five in Hampton cleaned by mild detergent solution. These were included because there was a larger increase in lighting output for those luminaires compared to the ones in the same location cleaned with 70% IPA. Since it is unknown whether this difference was caused by the cleaning or a difference in the dirt accumulated, both sets from Hampton were included. An outlier luminaire was excluded from the related study samples because it appeared that the average illuminance increased by 10%. This table includes the LED and luminaire optics, location, age, AADT, and the statistical summary of the illuminance data collected and errors for the data.

The table is sorted in order of luminaire design and then installation age. Luminaire designs and manufacturers were assigned letter values arbitrarily to identify them. Ten designs (models) and eight manufacturers were included in the study. Four types of LED optics and three types of luminaire optics are represented.

The largest data set is the Design A luminaire, with 24 luminaires included in the study with installation ages of 3, 6, and 7 years. Design A luminaires were found at all but the Charleston site. This luminaire has individually molded optics and no luminaire optics. The table also details summary statistics for the horizontal illuminance collected for these optics.

Average dirt depreciation is the average illuminance for a dirty luminaire or group of luminaires, divided by the average clean illuminance. The selection of the sample area for each of the averages was performed based on the GPS coordinates of the luminaires identified in the clean data set. That way any shift in the pattern of the luminaires would be captured in the statistics.

Maximum dirt depreciation is the dirt depreciation at the point of highest illuminance in the clean data set. Uniformity was calculated for each luminaire or average uniformity was calculated for each set of luminaires, both dirty and clean, and then the ratio of dirty to clean was calculated for the column “Uniformity Change” in the table.

The column, “Dirt Depr. Std. Error” is the standard error for the average and maximum dirt depreciation calculations in each row. The “Uniformity Std. Error” column is the standard error for the uniformity calculation.

Table 6. Dirt Depreciation Data for All Data Sets

Design	Manufacturer	LED Optics	Luminaire Optics	Avg. Dirt Depr.	Max Dirt Depr.	Uniformity Change	Number of Luminaires	Dirt Dep. Std. Err.	Uniformity Std. Error	Location	Installation Age, yrs.	AADT
A	E	Individual Molded Acrylic	None	86.9%	97.5%	100.0%	10.00	2.1%	11.7%	I - 35W Bridge	7	280000
A	E	Individual Molded Acrylic	None	96.1%	96.6%	114.3%	5.00	1.5%	7.4%	Hampton	3	86000
A	E	Individual Molded Acrylic	None	88.8%	97.4%	136.7%	5.00	1.4%	7.4%	Hampton	3	86000
A	E	Individual Molded Acrylic	None	77.2%	84.1%	71.6%	2.00	1.8%	14.8%	Smart 2	6	20
A	E	Individual Molded Acrylic	None	99.3%	97.9%	106.4%	1.00	2.3%	10.4%	Park and Ride	3	553
A	E	Individual Molded Acrylic	None	100.3%	95.4%	96.5%	1.00	2.3%	8.1%	Park and Ride	3	553
B	F	Molded Acrylic	Flat Glass	99.1%	98.6%	102.6%	1.00	3.6%	18.1%	Park and Ride	3	553
B	F	Molded Acrylic	Flat Glass	98.8%	98.8%	93.6%	1.00	3.5%	15.9%	Park and Ride	3	553
C	G	Molded Acrylic	Flat Glass	100.3%	100.2%	98.0%	1.00	5.3%	95.8%	Park and Ride	3	553
C	G	Molded Acrylic	Flat Glass	96.5%	99.0%	127.0%	1.00	5.1%	124%	Park and Ride	3	553
D	H	Individual Molded Acrylic	None	99.2%	95.1%	90.7%	1.00	2.3%	28.4%	Park and Ride	3	553
E	I	Individual Molded Acrylic	Flat Glass	97.4%	99.2%	119.8%	1.00	3.8%	55.5%	Park and Ride	3	553
E	I	Individual Molded Acrylic	Flat Glass	99.9%	100.4%	99.4%	1.00	4.1%	68.6%	Park and Ride	3	553
F	A	Molded Glass	White Reflector	90.9%	83.7%	101.3%	9.00	1.6%	4.4%	WV - 61	4	22000
F	A	Molded Glass	White Reflector	88.8%	91.3%	103.2%	3.00	3.2%	8.7%	I - 77	5	68500
G	B	Individual Molded Acrylic	None	62.6%	58.5%	99.4%	2.00	3.1%	10.3%	I - 77	5	68500
J	C	Molded Acrylic	Flat Glass	91.2%	97.6%	112.1%	3.00	6.2%	21.1%	I - 77	5	68500
K	B	Large Molded Individual Acrylic	None	80.8%	88.5%	96.2%	1.00	5.6%	25.4%	I - 77	5	68500
L	E	Individual Molded Acrylic	Flat Glass	95.6%	97.9%	92.4%	2.00	4.1%	8.9%	I - 77	5	68500
HPS	B	None	Flat Glass	95.1%	98.7%	94.9%	1.00	5.4%	124%	Park and Ride	3	553

ANALYSIS

The data are presented graphically in Figure 62, which shows average dirt depreciation versus age of installation. While the data are fairly tightly grouped at 3 years of installation, the variance in the data is quite large at 5 years. The data at 4 years, 6 years, and 7 years each represent just one type of luminaire each at a separate location. The overall loss rate is 2.3% per year. The data correlation is not strong, with an R^2 of only 0.29, indicating that other driving factors are present.

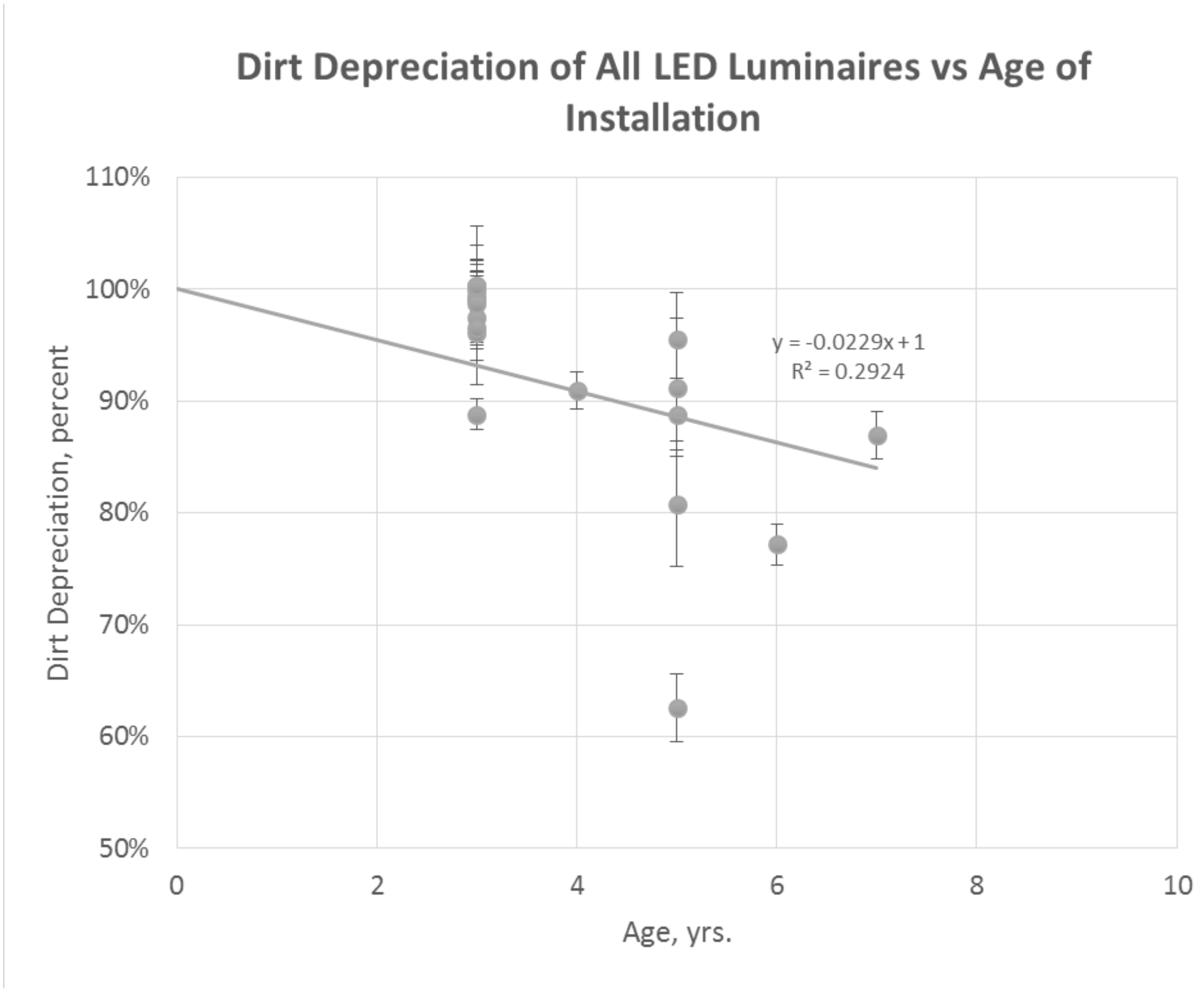


Figure 62. Average dirt depreciation vs. age for all LED luminaires sampled.

Analysis of the dirt depreciation at the maximum illuminance location is shown in Figure 63. The data are again fit with a linear model. In this case, the loss rate is lower at 1.8% per year, but with an R^2 value of 0.13, indicating a worse fit of the data and thus more variance. This is further evidence that a single value for dirt depreciation of a luminaire is not valid and that uniformity changes with dirt depreciation.

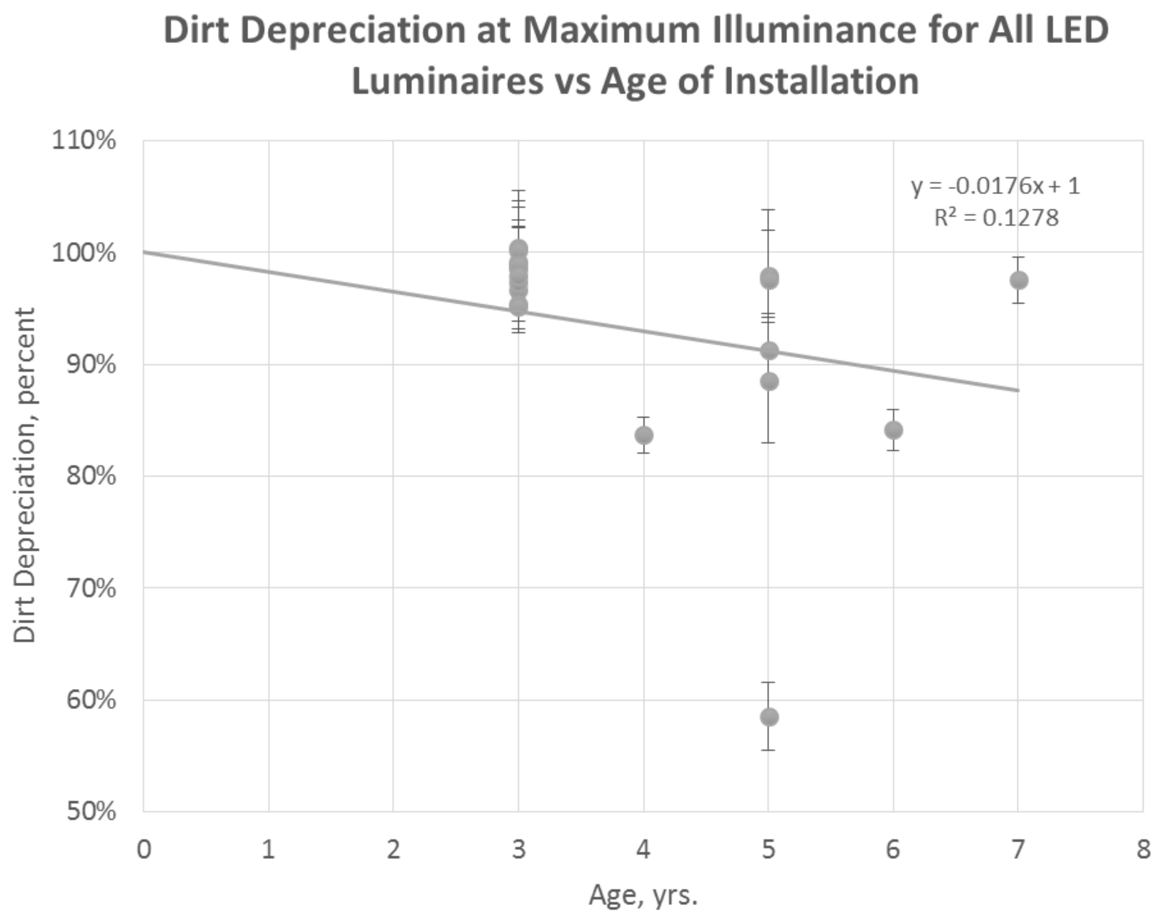


Figure 63. Dirt depreciation at maximum illuminance vs. age for all LED luminaires sampled.

The change in uniformity is shown in Figure 64. This figure shows that change in uniformity does not correlate well with age. In fact, the negative R^2 value indicates a different fit is needed. Other simple models were tried, but none would pass through 100% at zero years and have a positive R^2.

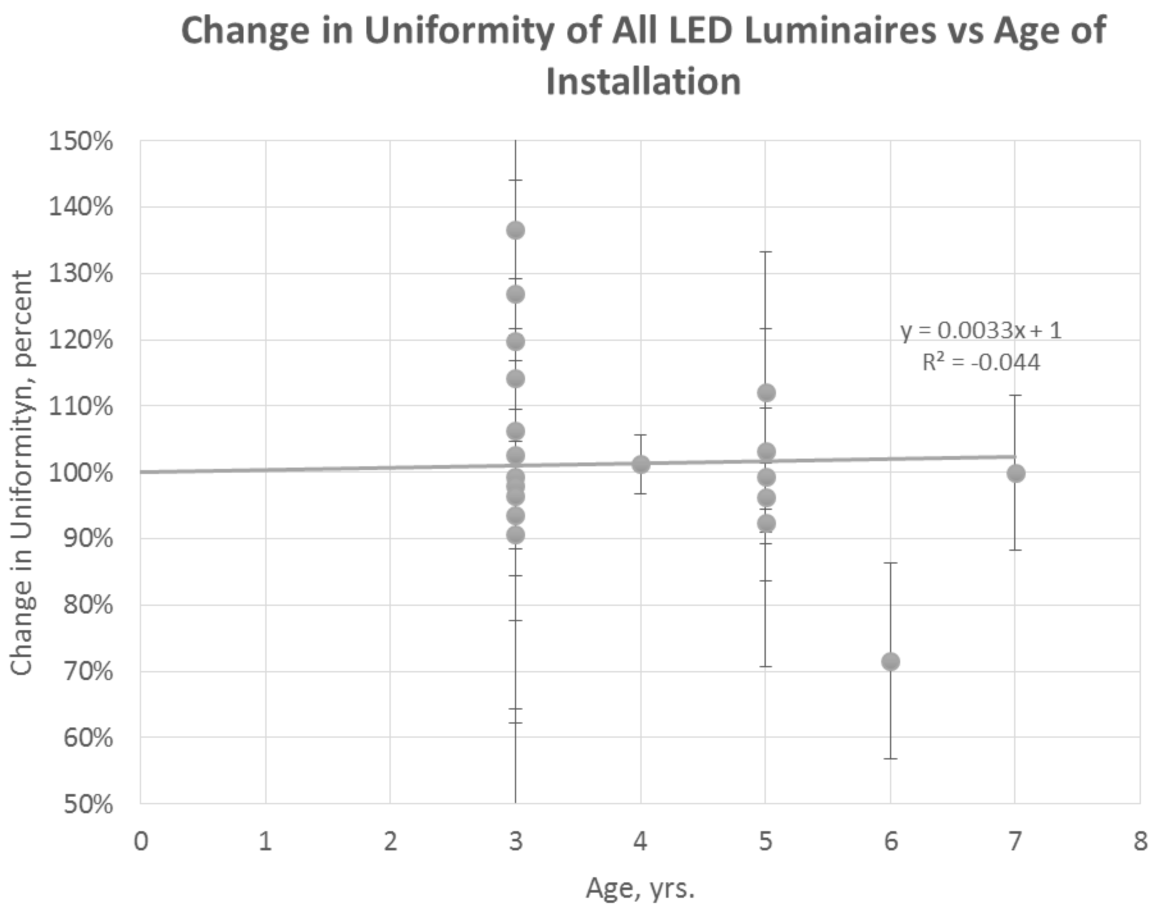


Figure 64. Change in uniformity vs. age for all LED luminaires sampled.

Analyzing the average dirt depreciation against AADT shows a poor correlation with a linear fit as well, again with a negative R^2 (Figure 65). This is another good indicator that multiple factors are responsible.

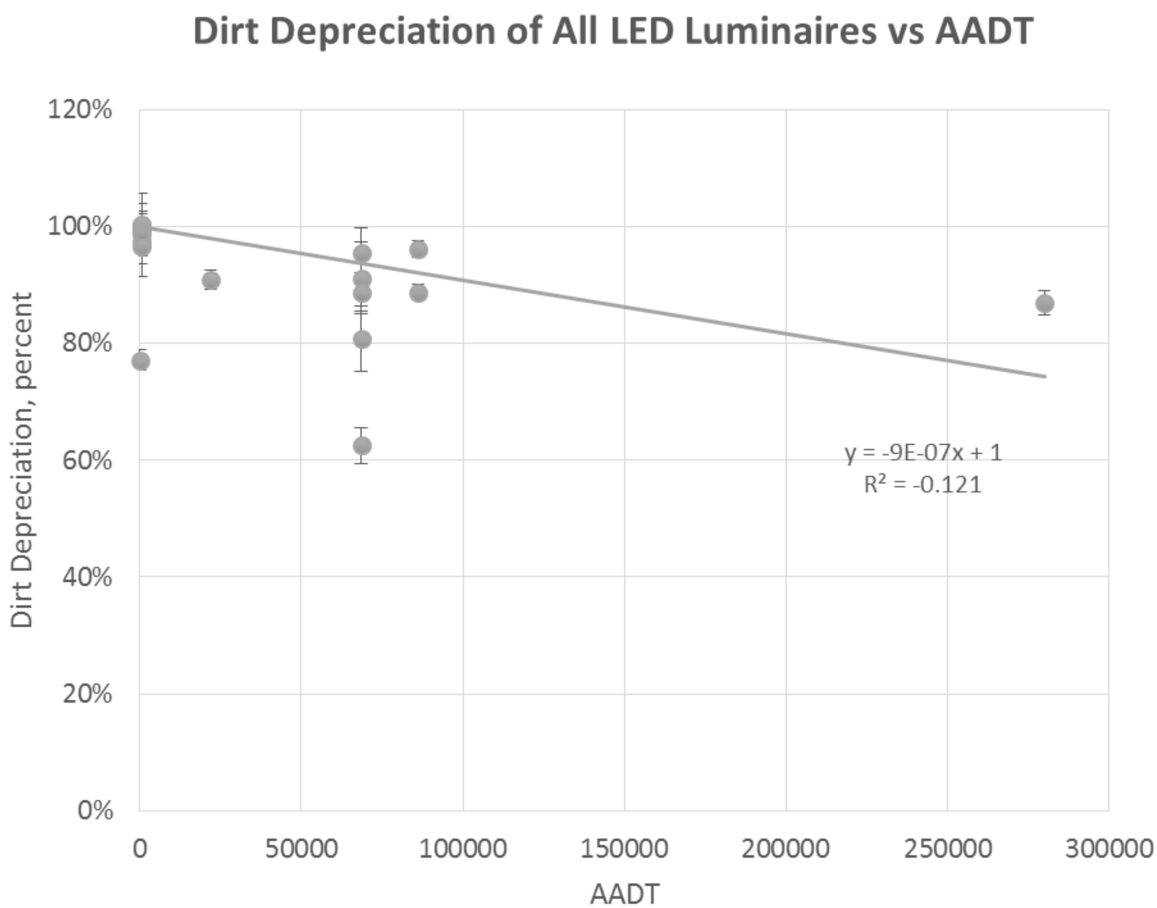


Figure 65. Average dirt depreciation vs. AADT for all LED luminaires sampled.

If the luminaires with exposed individually molded acrylic optics, the largest data set, are analyzed separately from the other optics types, the slope of a linear fit becomes a little steeper at 3.0% per year (Figure 66) versus 2.3% per year for the full data set. The R^2 value improves to 0.32, indicating a marginally better fit. The remaining scatter may be due to difference in the dirt that accumulates at each location, which is not easily separable from age or AADT due to the sparsity of the data set. While not reproduced here, the dirt depreciation at maximum illuminance versus age, uniformity change versus age, and average dirt depreciation versus AADT for only the luminaires with individually molded optics and no luminaire optics show no better correlation to linear models than the full data set.

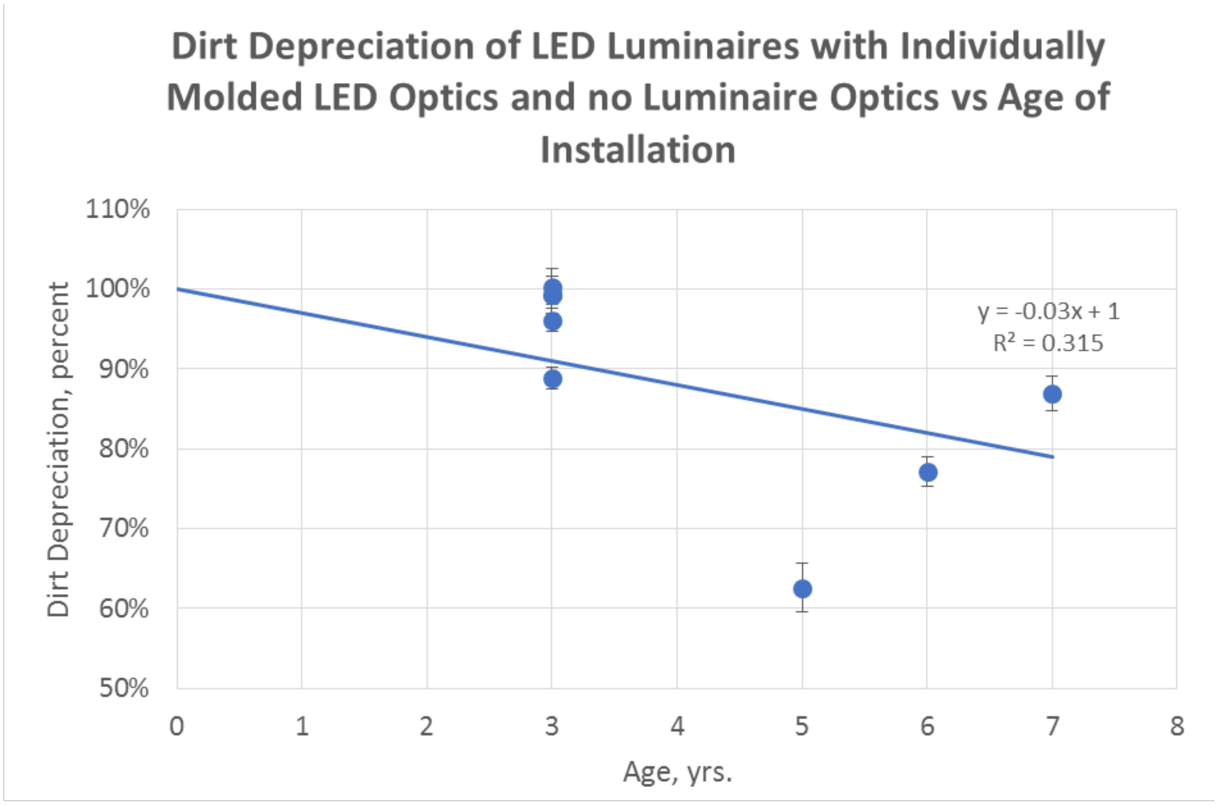


Figure 66. Dirt depreciation for individual molded acrylic optics and no luminaire optics (i.e., Designs A, D, and G).

Figure 67 shows the dirt depreciation rate as a function of time for two groupings of outer optics, flat glass and none. The luminaires with the white reflectors, Design F, were grouped with the other luminaires without a flat glass outer optic. The data clearly show a difference in dirt depreciation rate for the two groups, 0.9% loss per year for the flat glass outer optics and 2.1% per year for those without outer optics.

In this case, it appears that the LED luminaires with flat glass protecting the molded optics have a lower dirt depreciation rate than the exposed individual optics. This could be explained by the larger surface area and by the more complex airflow over the exposed molded optics than the flat glass. There also seems to be less variation in the luminaires with a flat glass luminaire optic, but the limited variation in LED luminaire types in older installations makes this difficult to analyze.

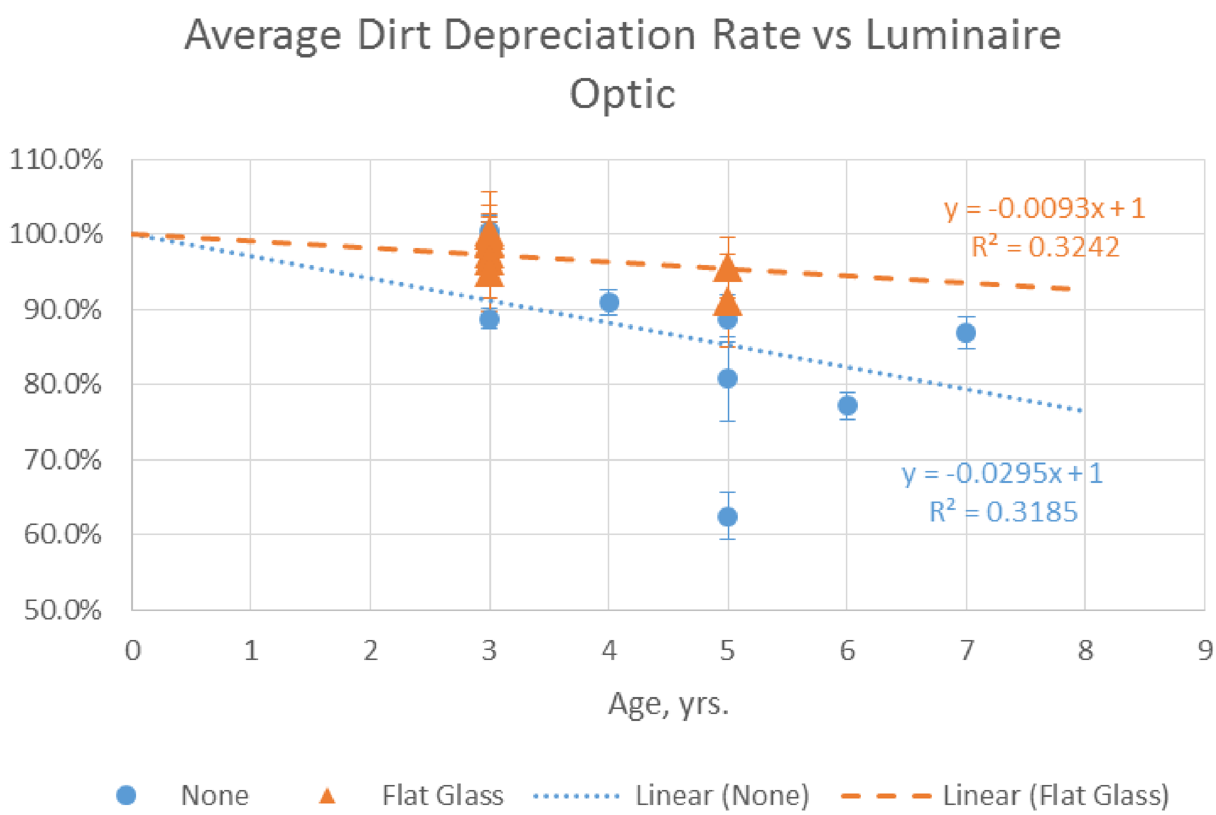


Figure 67. Average dirt depreciation rate vs. age for all samples versus the outer optic, categorized into flat glass or none.

If the change in illuminance at the location of maximum illuminance is analyzed for dirt depreciation, the data show similar trends but a lower dirt depreciation rate (Figure 68) for each luminaire outer optic category. The data show a 0.3% per year dirt depreciation rate for luminaires with flat glass outer optics, and a 1.7% per year dirt depreciation rate for luminaires without outer optics. Therefore, at least relative to the outer optics, the dirt depreciation at the maximum illuminance location is not a good indicator of the full dirt depreciation.

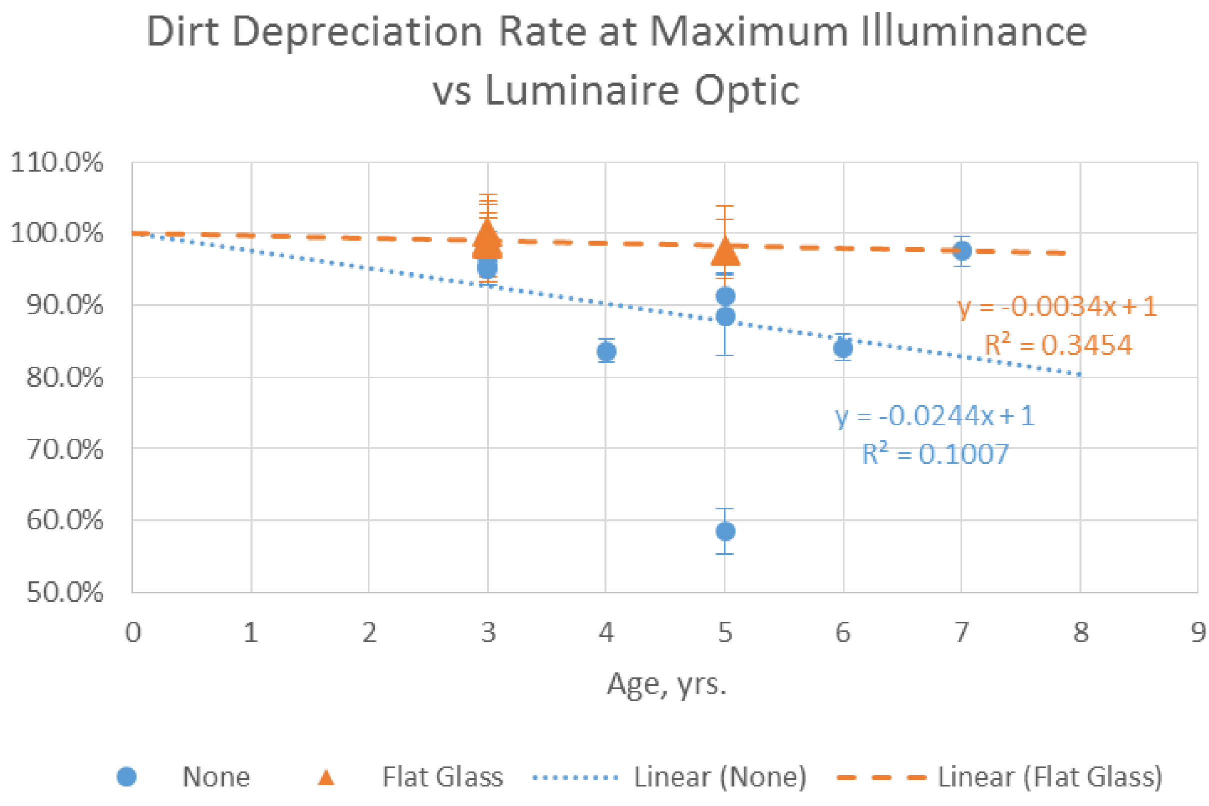


Figure 68. Maximum illuminance location dirt depreciation rate vs. age for all samples vs. the outer optic, categorized into flat glass or none.

In agreement with the dirt depreciation discrepancy between the average and maximum illuminance locations, the uniformity changes with dirt depreciation. As shown in Figure 69, the uniformity ratio of LED luminaires with a flat glass outer optic increases, indicating less uniformity. Luminaires with exposed LED optics, regardless of the optical material or size scale, experience a decrease in uniformity ratio, indicating an increase in uniformity.

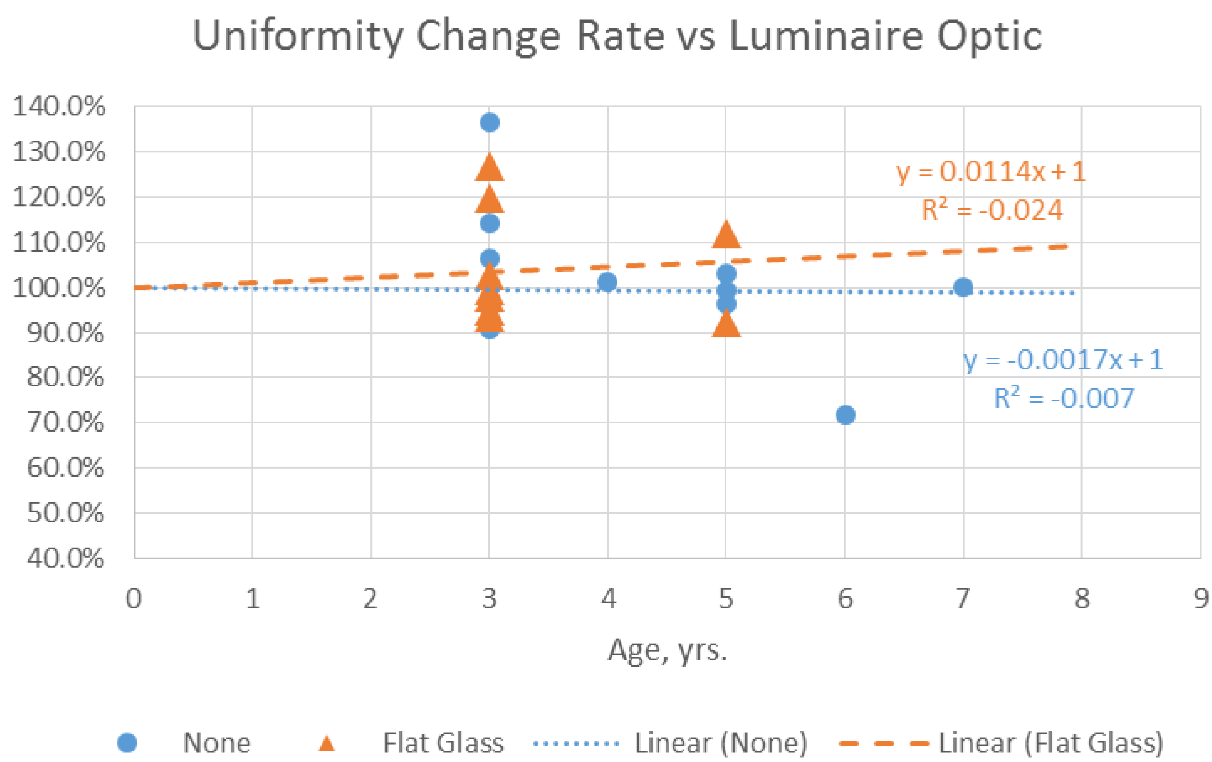


Figure 69. Uniformity change rate vs. age for all samples vs. the outer optic, categorized into flat glass or none.

Figure 70 shows that there is also a difference in dirt depreciation rate based on the type of inner optics. As can be seen, the rate of dirt depreciation is:

- 1.0% per year for molded acrylic;
- 2.5% per year for individually molded acrylic;
- 2.2% per year for molded glass; and
- 3.8% per year for large individually molded acrylic optics.

However, these data are not very deep in terms of sample size since there were only two installations of molded glass luminaires, one installation 4 years old (9 luminaires sampled), and another 5 years old (2 luminaires sampled) and one sample of one luminaire for the large individually molded acrylic optics.

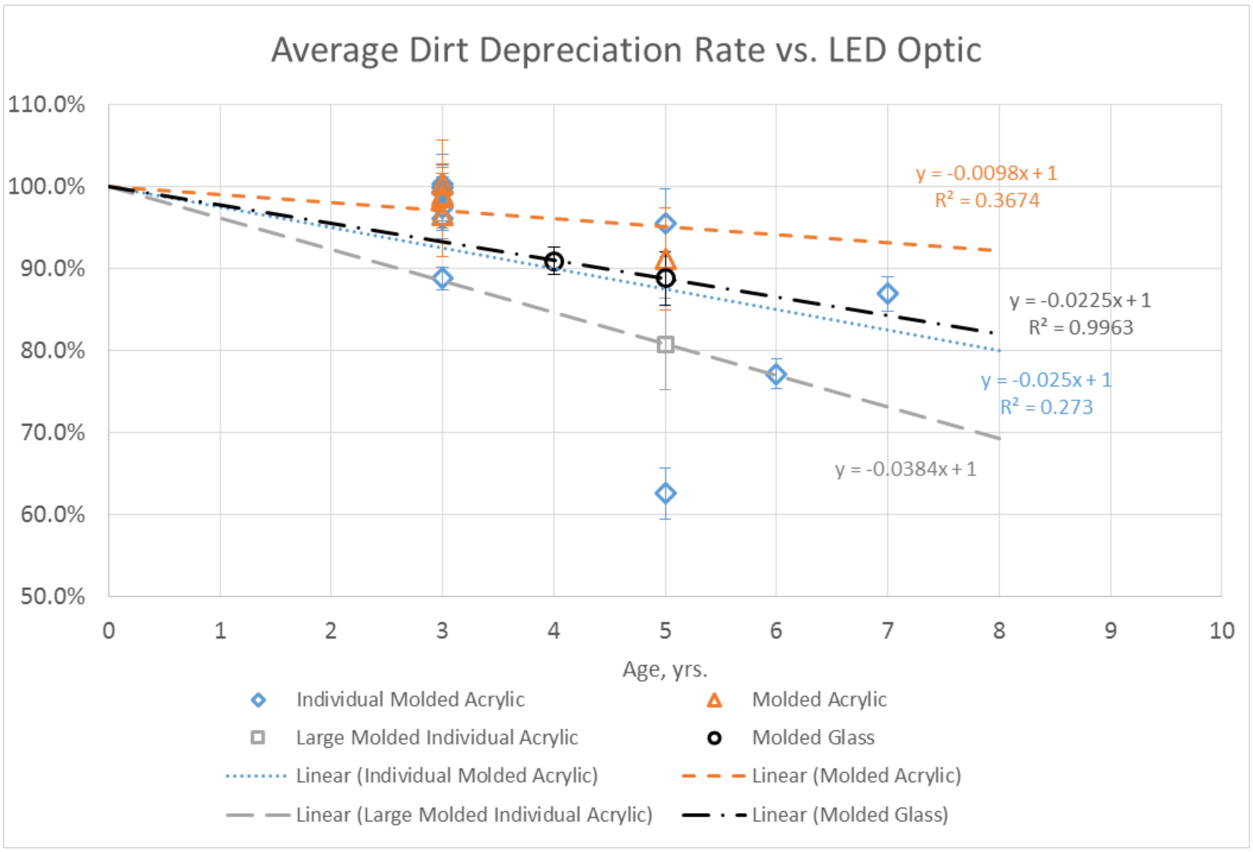


Figure 70. Average dirt depreciation rate vs. age for all samples vs. the inner optic.

Again, the change in the maximum value of the horizontal illuminance underpredicts the dirt depreciation (Figure 71).

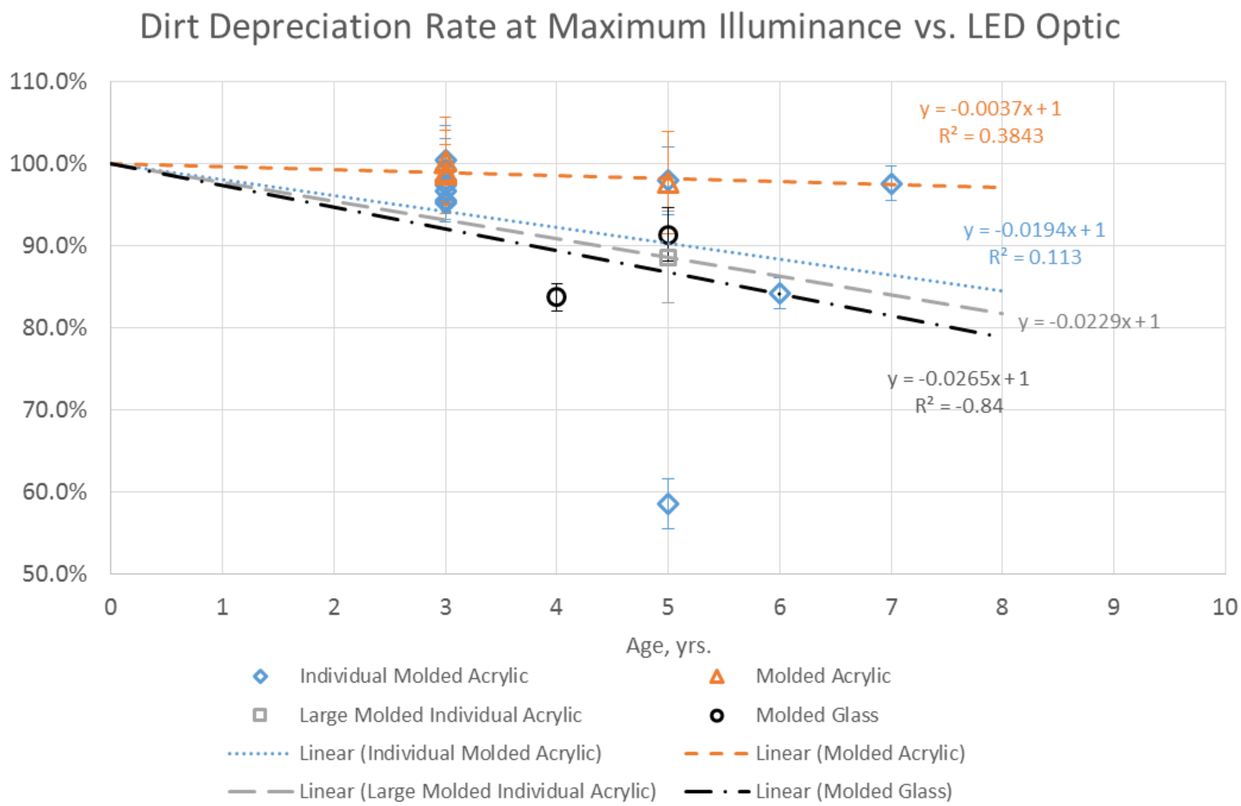


Figure 71. Maximum dirt depreciation rate vs. age for all samples vs. the inner optic.

The uniformity rate of change is less linear and has significantly more variance. Linear rates were fitted to the data and are shown in Figure 72. The luminaires with the least change in uniformity were the ones with the molded glass inner optics. The luminaires with the individual molded acrylic and molded acrylic both had large changes in the uniformity. Interestingly, the individually molded acrylic and large molded acrylic luminaires had uniformity ratios that improved with dirt depreciation, while the molded acrylic inner optics (with flat glass outer optics) had uniformity ratios that worsened with dirt depreciation (became higher numerically). However, as can be seen, the R^2 values are low except for the molded glass optics. The errors for each uniformity ratio were very large and are not shown on the graph. Therefore, these data should be considered very carefully.

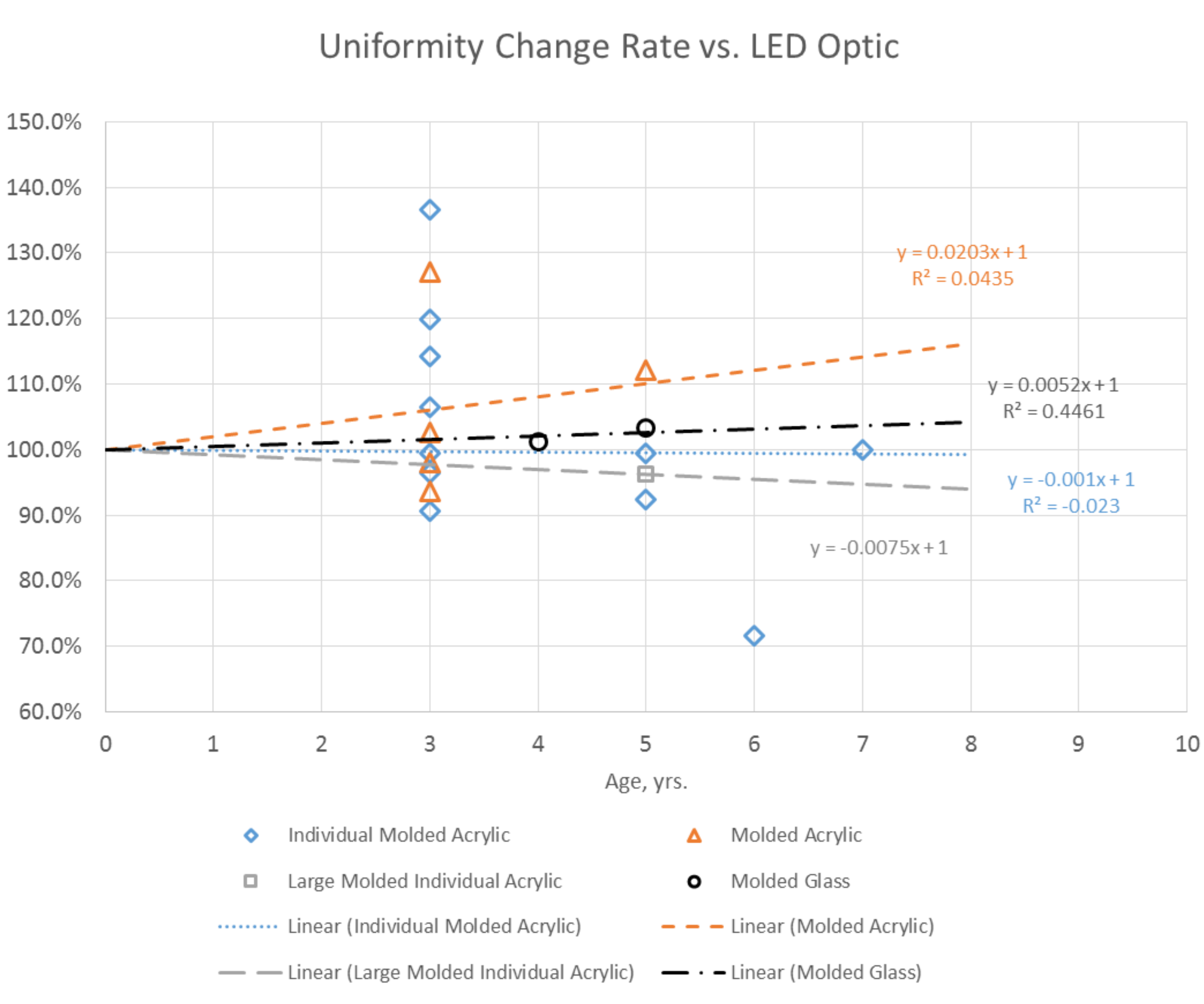


Figure 72. Average uniformity change rate vs. inner optics.

DISCUSSION

This study gathered data on dirt depreciation for a variety of LED luminaire designs of differing ages and in several different environments. The study found some trends regarding the dirt deprecation rates relative to both the inner and outer optics, even when the outer optics protect the inner optics. There also appears to be some correlation of dirt depreciation with AADT as well. However, the dirt depreciation rate with AADT was not strong either. The in situ measurement locations have differences in the percentage of truck traffic, salt spray during winter, proximity to water, and rainy days, resulting in different levels of "dirtiness" that are covariant with the AADT and age. More study is warranted to better determine the relationship between dirt depreciation, LED optics, luminaire optics, age, and environment for LED roadway lighting.

A solution of 70% IPA was found to be very good at cleaning luminaires, except when the environment had significant salt (near the oceans), in which case mild detergent performed better at cleaning. This corresponds to basic chemistry, where organic solvents are better at removing organic materials such as unburned hydrocarbons, while polar solvents (water) are better for removing polar molecules (salt).

LED luminaires with flat glass optics were less susceptible to average dirt depreciation than luminaires with exposed inner optics. The depreciation rate was 0.9% per year for flat glass outer optics versus 3.0% per year for exposed optics. The trends for uniformity were different for flat glass outer optics and no outer optics as well as for each inner optic type.

Another result of the research was that the dirt depreciation measured directly under the luminaire underestimates the total loss of light from the luminaire. This is due to changes in the pattern of the light distribution that was found in all of the LED luminaire samples. The pattern change varied with location, even within a single parking lot, so modeling and predicting the pattern change needs more study.

The difference is likely due to two factors: (1) the size scale of the feature predominant on the outermost optics of the luminaires and the resulting aerodynamics, and (2) the material composition of the outer optic. With flat glass optics, the outermost feature is flat, usually with a retaining "ring" which is rectangular and recesses the plate. With exposed optics, especially the individually molded acrylic, the surface of the optic is much more complex, has significantly more leeward edges, and significantly more surface area. These features will cause much more turbulence over the exposed optics, enabling dirt to accumulate on each individual optic and likely leading to more dirt sticking.

In addition, there is a difference between the contact angles of water on glass as opposed to acrylic. Clean glass has a relatively low contact angle of 25–29 degrees (Texas, 2015). PMMA (acrylic, Plexiglas) has a contact angle of 70.9 degrees (Enterprises, 2015). Given the hydrophobic properties of surfaces with higher contact angles, the results would seem counterintuitive except that there are also unburnt hydrocarbons and salt in the water in the vicinity of roadways. Thus, the contact angles may not be representative of the actual contact angle in situ because the surfaces are not clean. However, there will be a difference between the materials in similar conditions.

The dirt depreciation rate versus inner optics is more complex because of the influence of the outer optics. However, it does seem that individually molded acrylic inner optics and molded glass inner optics are similar in dirt depreciation rates at approximately 2% to 2.5% per year. Molded acrylic inner optics with multiple LEDs under a single optic seem to have the lowest dirt depreciation rate, but all of these samples included in this analysis had flat glass outer optics, a confounding factor. The worst dirt depreciation was for the large, individually molded acrylic inner optic luminaire. This may be because the features of this optic were on the order of tens of millimeters in vertical height, as compared to only 2 to 4 millimeters for the other optic types.

The changes in uniformity of the light due to dirt depreciation versus inner optic is again confounded by the outer optics. The sampled luminaires did not include the combinations of molded acrylic over several LED sources without an outer optic of flat glass and did not include any molded glass optics covered by an outer flat glass optic. Nevertheless, the uniformity change rates for molded glass optics and large individually molded acrylic optics were near zero. The uniformity change rate for individually molded acrylic inner optics decreased, meaning uniformity decreased (became more uniform) at a rate of 0.8% per year, while molded acrylic uniformity increased (became less uniform) at a rate of 2.0% per year.

CONCLUSION AND RECOMMENDATIONS

In general, the dirt depreciation rate for LED luminaires is different from high intensity discharge (HID) luminaires. Based on the data collected here, designers and maintainers should consider that dirt depreciation could be significant as installation age approaches 15 years. The outer optic has a significant effect on the dirt depreciation rate that affects not only the total light being emitted but also the distribution of the light.

However, this study was not able to ascertain what effect the level of “dirtiness” or the percentage of truck traffic has on the dirt depreciation for LED luminaires. More study is required to separate these effects and to isolate the additional factors causing the low correlation values. More samples of the same luminaire (or similar optic designs) at additional installation ages are also needed to determine the shape of the curve for dirt deprecation for LED luminaires. This study only provides enough samples for linear models.

That being said, the authors feel confident in suggesting some recommendations. For LED luminaire dirt depreciation, designers and maintainers should consider at a minimum the type of outer optic on the luminaire as the driver for the dirt deprecation rate according to the table below (Table 7).

Table 7. Recommendations for Dirt Depreciation vs. Outer Optic

Luminaire Optic	Dirt Depreciation Rate	Uniformity Change Rate
Flat glass	+1% per year	+1% per year
None	+3% per year	0% per year

If a more complex analysis or finer precision is needed, inner optics must also be considered. For example, in Figure 66 only the luminaires with exposed individually molded acrylic optics were considered. Those luminaires had a dirt depreciation rate of 3% per year. Unfortunately, there were insufficient samples to consider each luminaire design individually. Therefore, the following chart should be used (Table 8). Due to the low correlation rates, no recommendation for uniformity change with respect to LED optic is suggested at this time.

Table 8. Dirt Depreciation Rate vs. LED Optics

LED Optic	Dirt Depreciation Rate
Individually molded acrylic	1.8% per year
Molded acrylic	1.0% per year
Large individually molded acrylic	3.8% per year
Molded glass	2.2% per year
Individually molded acrylic with no outer optics	3.0% per year

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