Street Lighting and Public Safety: New Nighttime Lighting Documentation Method

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ABSTRACT: While the rapid transition of street lighting technologies is occurring across the country for its promising benefits of high energy efficiency, higher intensity, long lamp life, and low maintenance, there is a lack of understanding on the impacts from street lighting's physical characteristics on public safety. Nighttime lighting and its impact on the incidence of crime and roadway accidents has been investigated since the 1960s in the United States and the United Kingdom. However, prior research has not presented any scientific evidence such as quantified lighting characteristic data and its impacts on public safety because they relied on subjective survey inputs or over-simplified quantification of nighttime lighting conditions. To overcome the limitation of previous studies, extensive documentation of street lighting characteristics was conducted in downtown San Antonio, Texas, which adopts both conventional and new street lighting technologies. Two different sets of light level data were collected on roadways in order to measure the amount of light falling on the ground and on drivers' eyes inside a car. Correlated color temperature and a color rendering index of nighttime lighting were recorded. The collected lighting data was mapped in a Geographic Information Systems database in order to spatially analyze lighting characteristics. The paper first highlights the potential issues with lighting analysis in previous studies. Next, the proposed research methodology to address these issues for both data collection and spatial analyses is explained. Finally, the preliminary documentation and analysis of street lighting characteristics are presented.

KEYWORDS: street lighting, public safety, nighttime environment, LED, High Pressure Sodium

INTRODUCTION

Currently, 10% of existing street lighting in the United States has been converted to Light Emitting Diode (LED) lighting technology with promising benefits for energy efficiency, higher intensity, long lamp life, and low maintenance (Kraus, 2016). While the rapid transition of street lighting technologies from conventional high pressure sodium (HPS) or metal halide (MH) to LED occurs across the country, there is lack of understanding on the impacts from street lighting's physical characteristics on public safety and security. Nighttime lighting and its impact on the incidence of crime and roadway accidents has been investigated since the 1960s in the United States and the United Kingdom. Previous research claims that brighter nighttime lighting environments do not simply guarantee positive impacts on public safety at night. On the contrary, excessive and uncontrolled street lighting can even cause negative impacts to communities. Discomfort or disability glare from unshielded or poorly designed street lighting can reduce human eye visibility at night that eventually decreases levels of safety and creates roadway hazards (Gibbons and Edwards, 2007; Lin et. al., 2014; Tyukhova, 2015). In 2016, the American Medical Association (AMA) Council on Science and Public Health concluded that pervasive use of nighttime lighting creates potentially harmful effects related to discomfort and disability glare and addressed the urgent need for more extensive research on lighting's impact on human health and safety, particularly in the rapid transitions and installations of new lighting technology (Kraus, 2016).

After reviewing a number of previous research studies on the topic, two potential issues were identified. First, the studies misinterpreted increased light levels or increased number of street lighting as improved nighttime lighting conditions. This oversimplified interpretation of improved nighttime lighting conditions caused other important lighting characteristics to be overlooked. Improvement of the nighttime lighting environment should be determined by a level of nighttime visibility and visual comfort instead of the number of streetlight poles. Secondly, subjective survey inputs from community residents were relied on without collecting and analyzing quantifiable lighting characteristics such as illuminance, luminance, uniformity, color temperature, and the color rendering index. For instance, a Chicago Alley Lighting Project study considered how many new lighting fixtures were added to an experimental area compared to a controlled area. No fixture location, illuminance levels, uniformity, color temperature, and beam optic data were documented or analyzed (Morrow and Hutton, 2000). Also, the AMA report was generated by literature reviews and lab tests without collecting or measuring physical characteristics of street lighting such as light spectrum, amount of light, duration of exposure, spatial distribution, and timing (Rea and Figueiro, 2016). These examples clearly show that more in-depth analysis on physical characteristics of lighting is required to truly understand street lighting's role on public safety.

Across the United States, there is on-going efforts to improve nighttime lighting environments and energy efficiency. Recently developed communities already have advanced lighting systems such as LED lighting technology to provide a higher energy efficiency and longer life while conventional lighting technologies, such as HPS or normal MH, are common in existing communities. However, existing communities have been rapidly replacing conventional lighting to new lighting technology. It is imperative to fully understand the impacts and consequences from this lighting transition. To overcome the limitation of previous studies, extensive documentation of street lighting characteristics was conducted in downtown San Antonio, Texas, which adopts both conventional and new street lighting technologies. Two different sets of light level data were collected on roadways in order to measure the amount of light falling on the ground and on a drivers' eyes inside a car. Correlated color temperature and a color rendering index of nighttime lighting were recorded. The collected lighting data was mapped in a Geographic Information Systems database in order to spatially analyze lighting characteristics.

The City of San Antonio has a city-wide street lighting redevelopment plan which will eventually introduce new LED lighting technology throughout the entire city. This redevelopment project provides an opportunity to use San Antonio as a case study. While the redevelopment plan is being implemented, the City of San Antonio has also created a working group to evaluate and develop a new dark sky policy in San Antonio. Dark sky is a worldwide effort to minimize the negative influence of street and architectural lighting on nighttime environments. The policy has been incorporated into the building codes and standards of major cities. It is crucial to measure the current status of nighttime lighting conditions in San Antonio and to evaluate the need for new guidelines to limit the amount of man-made light pollution into the nighttime sky. The findings from the study will also help validate and improve existing lighting guidelines of roadways, sidewalks, and public spaces.

EXISTING STREETLIGHT GUILDELINES

Currently, street lighting design and installations are determined by the pre-determined horizontal illuminance levels and uniformity ratios on roadways and sidewalks, which were developed by the Illuminating Engineering Society of North America (IESNA) and approved by the American National Standards Institute (ANSI). ANSI/IESNA RP-8-00 Roadway Lighting Guidance recommends to provide a range of 3.0 to 17.0 lux of average maintained horizontal illuminance level on local, collector, and major roadways (Table 1). It also recommends the roadways to maintain 3:1, 4:1, or 6:1 uniformity ratio between average and minimum illuminance levels depending on roadway types. This recommendation varies depending on the roadway type, pedestrian conflict potential, and road pavement classifications (Table 1).

Table 1: American National Standard Practice for Roadway Lighting ANSI/IESNA RP-8-00

Road	*Pedestrian conflict area*	*Average maintained illuminance*			*Illuminance uniformity ratio E_{avg}/E_{min}*
		R1	R2/R3	*R4*	
Major	High	12.0 lux	17.0 lux	15.0 lux	3:1
	Medium	9.0 lux	13.0 lux	11.0 lux	
	Low	6.0 lux	9.0 lux	8.0 lux	
Collector	High	8.0 lux	12.0 lux	10.0 lux	4:1
	Medium	6.0 lux	9.0 lux	8.0 lux	
	Low	4.0 lux	6.0 lux	5.0 lux	
Local	High	6.0 lux	9.0 lux	8.0 lux	6:1
	Medium	5.0 lux	7.0 lux	6.0 lux	
	Low	3.0 lux	4.0 lux	4.0 lux	

Besides ANSI/IESNA RP-8-00 Roadway Lighting Guidance, American Association of State Highway and Transportation Officials (AASHTO) Roadway Lighting Design Guide is referenced when streetlights are designed and installed on roadways. It shows similar recommendations as ANSI/IESNA guidelines but there are slight differences in required illuminance levels and uniformity ratios. Based on the roadway classifications, including secondary arterial, collectors, and local roads, AASHTO recommends average maintained horizontal illuminance levels ranging from 3.0 lux to 14.0 lux (Table 2). Also, a 4:1 or 6:1 uniformity ratio between average and minimum illuminance levels is recommended.

Table 2: AASHTO Roadway Lighting Design Guide

Roadway classification	*General land use*	*Average maintained illuminance*			*Minimum illuminance*	*Illuminance uniformity ratio avg./min.(max)*
		R1	R2/R3	*R4*		
Minor Arterials	Commercial Intermediate Residential	9.0 lux 8.0 lux 5.0 lux	14.0 lux 10.0 lux 7.0 lux	10.0 lux 9.0 lux 7.0 lux	As uniformity ratio allows	4:1
Collectors	Commercial Intermediate Residential	8.0 lux 6.0 lux 4.0 lux	11.0 lux 8.0 lux 6.0 lux	9.0 lux 8.0 lux 5.0 lux	As uniformity ratio allows	4:1
Local	Commercial Intermediate Residential	6.0 lux 5.0 lux 3.0 lux	8.0 lux 7.0 lux 4.0 lux	8.0 lux 6.0 lux 4.0 lux	As uniformity ratio allows	6:1

These existing guidelines are effective to determine the efficiency and evenness of street lighting design and installations. However, the guidelines do not consider the human biological response such as the level of visibility, potential discomfort or disability glare, light color perception, etc. In other words, public safety of nighttime environments cannot be guaranteed or ensured by simply meeting the guidelines. Other critical factors such as light color temperature, the color rendering index, and vertical illuminance levels on people's face should be considered to increase and enhance safety at night.

METHODOLOGY

The objective of this project is to determine if a correlation between quantifiable street lighting characteristics and public safety exists. In order to achieve this objective, extensive documentation of street lighting characteristics is presented in this paper to understand the existing street lighting characteristics in downtown San Antonio neighborhoods (Figure 1). Neighborhoods in downtown San Antonio were selected based on the types and locations of existing street lighting. Surrounded by major express ways, the selected neighborhoods include various zoning districts such as downtown, commercial, industrial, infill development, and residential districts. Based on existing street lighting data provided by CPS Energy, the project has a mixture of conventional and new lighting technologies and various lighting characteristics. The existing nighttime lighting environments in the selected area are documented and evaluated in a GIS.

Based on the roadway classification of the City of San Antonio, the project scope includes the roadways classified as major (or arterials), collectors, and local roads. Santa Rosa Avenue, South Alamo Street, and Cesar Chavez Boulevard are examples of major roadways (arterials). The remaining roadways in the project scope are either collector or local roadways. Express ways are not included within the project boundary.

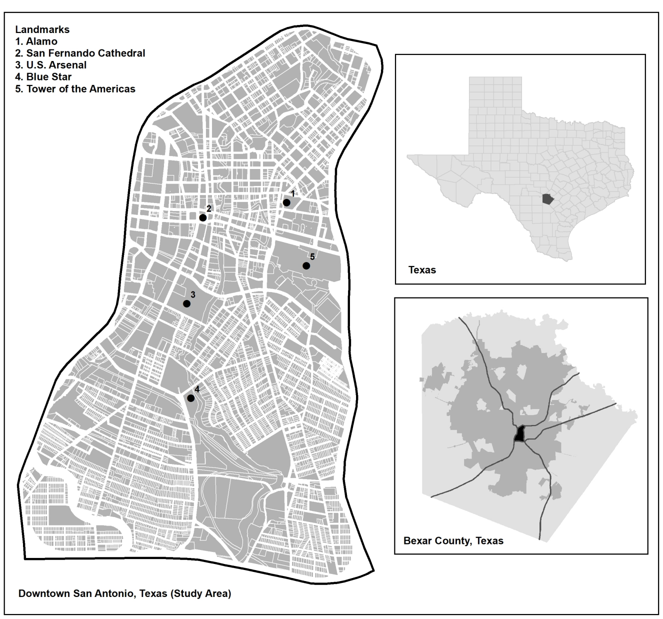

Figure 1: Selected project scope in downtown San Antonio

The following lighting documentation methodologies were utilized. Two different sets of light level data were collected on the roadways: horizontal illuminance levels at the ground level and vertical illuminance levels at the human eye height. These two illuminance data sets measure the amount of light falling on the ground and on the eyes of a driver inside a car. Correlated color temperature and a color rendering index of nighttime lighting is recorded at different locations within the project scope. The collected data was entered into the GIS database in order to analyze spatially the lighting characteristics which will be used in a future study to examine the relation to the incident rates and locations of both crime and roadway accidents.

For illuminance level measurements, one Li-Cor photometric sensor was mounted on a car to measure horizontal illuminance levels arriving on the roadway at 1 second intervals. Another Li-Cor photometric sensor was mounted inside a car simultaneously to measure vertical illuminance levels arriving at a driver's eye position. Both photometric sensors were connected to a Li-Cor LI-1500 data logger with a Global Positioning System (GPS) tracking function for data storage. Illuminance level measurements were made in multiple site visits during the nighttime. Driving routes were carefully planned by using Google Drive in order to avoid measuring the same roads multiple times and also to ensure driving directions and road closures in advance. The entire project scope was divided into seven different sections and a total of seven site measurements were made between November 1st, 2017 and December 14th, 2017. Each field measurement began after sunset (after 8:00PM) and took at least three hours to cover every single roads and alleyways in each section of the project scope.

Correlated color temperature and a color rendering index were measured by using Sekonic Spectromaster C-700. Different from the photometric sensors and datalogger utilized for illuminance measurements, the spectrometer is a hand-held device without data logging capability and GPS tracking function. Measurement locations were determined based on the streetlight types so that typical light color temperature and CRI values from each type of the streetlights can be recorded. Multiple measurements were made for each type of HPS, LED, MH, and Sodium Vapor streetlights. The ranges of measured color temperature and CRI values were then organized for analysis.

RESULTS AND ANALYSIS

Streetlight data obtained from CPS Energy was analyzed in order to understand the types of streetlight luminaires and their performance specifications. As of November 17th, 2017, a total of 119,714 streetlights exist in the City of San Antonio. Within the selected project scope of downtown San Antonio, a total of 3,061 streetlights have been installed. Table 3 shows the quantity and percent share of each installed streetlight lamp type including HPS, LED, MH, and Sodium Vapor. HPS streetlight is still a dominant type in the project scope. Currently, 32% of the total streetlights include various LED sources. The number of LEDs is expected to increase in the coming years due to the city-wide street lighting redevelopment plan.

Table 3: Streetlight lamp types in downtown San Antonio (CPS Energy 2017)

Lamp Type	*Count*	*Percent*
High Pressure Sodium	1,666	54.43%
LED	981	32.05%
Metal Halide	381	12.45%
Sodium Vapor	25	0.82%
Missing Data	8	0.26%

Different lamp wattages ranging from 100 Watts to 1,000 Watts are being used in the existing streetlights. HPS streetlight lamps are in 100W, 150W, 175W, 250W, 400W, and 1000W. MH streetlights are in 100W, 175W, 250W, and 400W. 40W, 96W, and 160W. LEDs were installed to replace the conventional HPS and MH streetlights. In prior studies, it was believed that a higher lamp wattage would improve nighttime lighting environments as it helps to make streets brighter. While lamp wattage determines lumen outputs from streetlights, it cannot be the only factor to determine whether nighttime lighting conditions are improved or not. Other lighting characteristics such as beam optic, color temperature, and CRI should also be considered to determine improved visual acuity and visual comfort at night.

Streetlight pole heights vary depending on the roadway types. Streetlights are mounted at 9.7 meters (32 ft) above ground at major and collector roadways while they are at 7.9 meters (26 ft) from the ground level on local roadways. Major roadways have 400W, collectors have 250W, and local roadways have 100W streetlights. The streetlight lamp specifications were also obtained from CPS Energy. HPS and LED streetlight specifications are described in Table 4. MH and Sodium Vapor streetlight specifications were not available.

Both HPS and LED streetlights are very efficient and generate around 100 lumens per watt. However, it is important to understand that initial lumens of HPS streetlights are lamp lumens, which are different from fixture lumens of LED streetlights. As light generated from HPS lamps passes through system enclosures, the amount of light decreases. It makes fixture lumens of HPS streetlights lower than fixture lumens of LED streetlights. HPS lamp color temperatures vary depending on manufacturers but it is known that HPS lamps typically produce very low (warm) light color temperatures around 2,500K and 2,700K with low color rendering index values. LED streetlights in the project scope have 4,100K correlated color temperature. Based on the specification comparisons, it is possible to conclude that LED streetlights are more energy efficient than HPS streetlights and also provide higher (cooler) color temperature and higher CRI values which help improve visual acuity in nighttime environments.

Table 4: Streetlight specifications of HPS and LED pole luminaires (CPS Energy 2017)

Lamp Type	*Watt*	*Lumens*	*Correlated color temperature*
High Pressure Sodium	100	9,500 (lamp)	N/A
	150	16,000 (lamp)	
	250	25,000 (lamp)	
	400	47,000 (lamp)	
LED	40	3,600 (fixture)	4,100K
	96	7,500 (fixture)	4,100K
	160	14,619 (fixture)	4,100K

Figure 2 shows streetlight types and locations within the project boundary. Red dots represent HPS streetlight locations and blue dots represent LED streetlights. Yellow dots are MH streetlights and purple dots are Sodium Vapor. All four types of streetlights are mixed in the downtown district (top half of the map). HPS and LED streetlights are randomly mixed in residential, commercial, and industrial districts (bottom half of the map). It is obvious that the downtown district has very dense streetlight installations on roadways compared to residential, commercial, and industrial districts. Based on the density of streetlight locations, it is possible to assume that there is a higher chance for over-illumination in the downtown district compared to the rest of areas. However, it is difficult to quantify actual illuminance levels or visual discomfort chances solely based on the map in Figure 2. In order to avoid overly simplified definitions of lighting conditions and to fully understand existing nighttime environment, accurate lighting data was measured on different roadways.

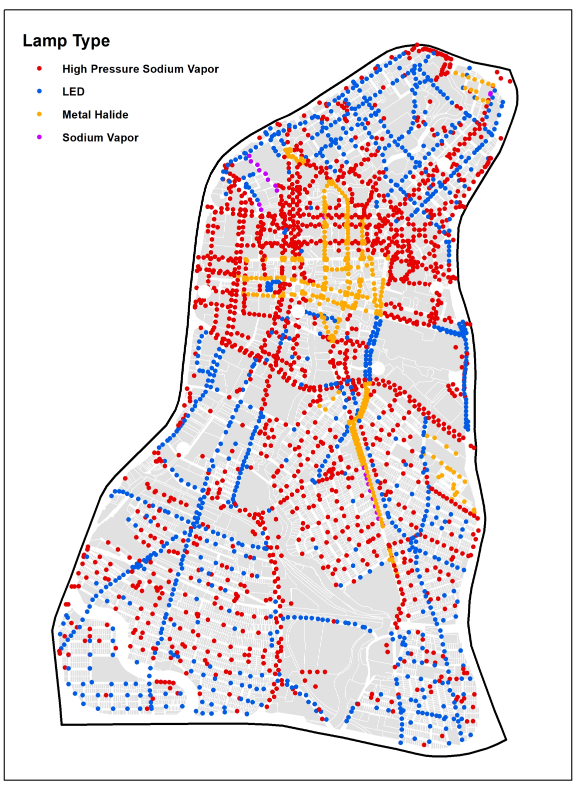

Figure 2: San Antonio Streetlight locations and types in the selected project scope

Collected illuminance data on roadways and driver's eyes were organized and the data were incorporated into ArcGIS software for analysis. Table 5 shows descriptive statistics of the collected illuminance data from the field measurements. Illuminance levels on roadways are not uniform as the range of illuminance levels on roadways is from 0.00 lux to 293.78 lux. Mean illuminance level on roadways is 13.43 lux, which is slightly brighter than what is required for local and collector roadways, but it is still an acceptable range for major roadways. Further statistical analysis is required to understand existing light levels in different land uses such as downtown, commercial, industrial, and residential districts. Different from the horizontal illuminance levels on roadways, collected vertical illuminance levels on driver's eyes show much lower light levels and less drastic contrast between minimum and maximum values. The mean vertical illuminance value of 2.35 lux shows that light level inside a car is much darker than what is available on roadways. The minimum value is still 0.00 lux while vertical illuminance level is up to 73.03 lux when incoming car headlight directly shines light towards driver's eyes. It is possible to assume that drastic changes of vertical illuminance levels on driver's eyes would negatively impact driver's night-time visibility and visual comfort while driving.

Table 5: Statistics of the collected illuminance levels within the entire project boundary

Value	*On roadways*	*On driver's eyes*
Mean illuminance	13.43 lux	2.35 lux
Median illuminance	6.43 lux	1.56 lux
Min. illuminance	0.00 lux	0.00 lux
Max. illuminance	293.78 lux	73.03 lux

The existing streetlight guidelines were referenced to check whether or not existing light levels in the project scope are sufficient and balanced. ANSI/IESNA RP-8-00 Roadway Lighting Guidance recommends local roadways to have a range of 4.0 to 9.0 lux of horizontal illuminance level on roadway, 6.0 to 12.0 lux for collectors, and 7.0 lux to 17.0 lux for major roadways. Based on these recommended illuminance levels and required uniformity ratios between average and minimum illuminance levels, it was possible to determine illuminance ranges for insufficient, acceptable (moderate), and excessive lighting conditions on various roadways. Based on the uniformity ratio 6 to 1, we can determine that illuminance levels below 0.66 lux is not sufficient for all roadway types. An illuminance range between 0.66 lux and 3.99 lux is lower than what is required but it is still acceptable for local and collector roadways. An illuminance range from 4.00 lux to 8.99 lux is appropriate for local and collector roadways. Also, it is an acceptable illuminance range for major roadways. An illuminance range between 9.00 lux and 17.00 lux is appropriate for major roadways but it is considered to be higher than what is required for local roadways. Illuminance levels above 17.00 lux may still be acceptable but it is unnecessary to provide this level of illumination for all three types of roadways.

Figure 3 illustrates existing illuminance levels on roadways. Different illuminance levels on roadways were color coded by the calculated illuminance ranges from the existing streetlight guidelines: 0.00-0.66 lux in blue (very low illuminance), 0.67-3.99 lux in green (low illuminance), 4.00-8.99 lux in yellow (moderate illuminance-local), 9.00-17.00 lux in orange (high illuminance-major), and above 17.00 lux in red (very high illuminance). As expected, a clear distinction between the downtown district and the rest of the neighborhoods can be made based on the nighttime lighting condition in Figure 3. The downtown district (the area inside the dashed white line) has much brighter nighttime lighting conditions than the rest of the areas in the project scope. Most of the roadways in the downtown district are either green, yellow, orange, or red in color, which represents acceptable or excessive lighting conditions. The roadways in either residential, commercial, or industrial districts have, in general, insufficient illuminance levels. Local roadways in residential and industrial districts are mostly in blue color, which shows that illuminance levels do not meet the required minimum light levels. Higher light levels are observed in intersections and also along the major and collector roadways. Further investigation is required to understand uniformity issues of different types of roadways and how this impacts public safety.

Figure 3: Collected street light level data mapped in ArcGIS

Besides the illuminance levels, correlated color temperature levels were collected from different locations of the project scope. Multiple measurements were made to record correlated color temperature ranges of each streetlight lamp type such as HPS, LED, MH, or Sodium Vapor. Locations of the measurements were determined based on the streetlight map. As expected, light color temperatures on roadways with HPS and Sodium Vapor streetlights are much lower than the ones with LED or MH (Table 6). Roadways with HPS and Sodium Vapor streetlights provide very warm (orange) light color that ranges from 1,800K to 2,600K. On the contrary, LED and MH streetlights provide cold (blue) light color that ranges from 3,900K to 9,300K. It is quite surprising that roadways with MH streetlights have light color temperatures up to 9,300K, which is an extremely cold light color. Color rendering index ranges are also shown in Table 6. LED streetlight shows the highest CRI values in a range of 74 to 78. MH streetlight also provides similar but a slightly lower color rendering index. HPS and SV streetlights show very low CRI values. As CRI values represent how different object and surface colors can be seen by our eyes, it determines human visibility at night. Human visibility is one of the most important factors that affect public safety. Therefore, the importance of good CRI light on roadways does not need to be highlighted again. The existing HPS and Sodium Vapor streetlights should be replaced by streetlights with a higher CRI value.

Table 6: Collected light color temperature and color rendering index (CRI)

Value	*Color temperature*	*Color rendering index*
High Pressure Sodium	1,963K-2,594K	14.9-41.9
LED	3,899K-4,370K	74.1-77.9
Metal Halide	4,190K-9,303K	62.6-76.9
Sodium Vapor	1,807K	-3.0

CONCLUSION

With the help of advanced lighting measurement technologies and a Geographic Information Systems (GIS) database, this study overcame the limitations of the previous studies by creating a database to analyze quantifiable data of nighttime lighting conditions. The new lighting data collection methodology allows for very detailed and accurate horizontal and vertical illuminance level measurements from all roadways within the project scope. The collected illuminance levels on roadways show that local roadways in residential and industrial districts do not have sufficient light levels to maintain visual acuity at night. On the contrary, the central downtown district currently has sufficient light levels on roadways but many of the roadways are overly illuminated by streetlights. Correlated color temperature and the color rendering index data helps to accurately describe the quality of existing nighttime lighting in downtown San Antonio. As stated earlier, this paper addresses the documentation of nighttime lighting environments. The next step is to investigate the collected roadway light levels in relation to crime data and roadway accident data. This investigation will help clarify the role of streetlight characteristics on public safety.

ACKNOWLEDGEMENTS

The authors appreciate the financial support we received for this project from the University of Texas at San Antonio Vice President Office of Research. We also thank CPS Energy for sharing detailed street lighting data.

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