Federal Aviation Administration

DOT/FAA/AM-22/08
Aviation Safety
Office of Aerospace Medicine
Washington, DC 20591

Light-Emitting Diodes in Airfield Lighting Applications: A Review and Annotated Bibliography

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September 2022

NOTICE

Technical Documentation Page

1. Report No. DOT/FAA/AM-22/08	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Light-Emitting Diodes in Airfield Lighting Applications: A Review and Annotated Bibliography		5. Report Date September 2022
		6. Performing Organization Code
7. Author(s) Peter T. Hu[1], Theodore C. Mofle[1], Christopher J. Dake[1], Kelene A. Fercho[2]		8. Performing Organization Report No.
9. Performing Organization Name and Address [1]Cherokee Nation 3-S [2]Civil Aerospace Medical Institute, FAA		10. Work Unit No. (TRAIS)
		11. Contract or Grant No.
12. Sponsoring Agency Name and Address Office of Aerospace Medicine Federal Aviation Administration 800 Independence Ave., S.W. Washington, DC 20591		13. Type of Report and Period Covered
		14. Sponsoring Agency Code
15. Supplementary Notes		

The primary objective of this report is to provide an overview of the available research literature on the use of light-emitting diodes (LEDs) for airfield lighting applications (e.g., runway, approach, taxi, apron lighting). These research efforts indicate several benefits of LEDs when compared to traditional incandescent or halogen lighting. LEDs tend to have a higher color saturation, which may provide a better opportunity to separate color boundaries and improve discriminability of airfield lights—this is particularly true during conditions such as fog or haze which tend to desaturate any light source color. LED-based approach lighting systems may be easier to detect at further distances, aiding in orienting a pilot to the runway environment sooner—particularly at nighttime or during reduced visibility conditions. LEDs have a much longer operating lifespan, which results in significant cost savings to airport operations budgets. As incandescent lamps become increasingly difficult to procure, switching to LED lighting ensures equipment and supplies are readily available to maintain airfield lighting infrastructure in the future. However, understanding how LED lighting may affect perceived brightness, perceived color, and compatibility with existing infrastructure and equipment are important safety considerations. Research indicates that LEDs may appear brighter than incandescent lighting, even when set to the same luminance levels—this is particularly a concern in certain weather conditions, such as fog. Although LED output can be adjusted to produce a brightness perceived to be similar to incandescent light sources, dimming LEDs may result in an undesired stroboscopic effect that is more likely to be experienced by pilots in single propeller aircraft. LEDs may not be compatible with certain flight deck vision technologies, such as Night Vision Imaging Systems (NVIS), Enhanced Flight Vision Systems (EFVS), or Enhanced Vision Systems (EVS), which may filter out and fail to display the wavelengths emitted by LEDs. Federal Aviation Administration (FAA) guidance materials have addressed many of the safety considerations identified in the research literature. Future research in the area of LED lighting for airfield applications is suggested, including the evaluation of additional environmental factors related to weather, and the inclusion of operationally relevant research designs. Thirty-nine references from 2001 to 2021 were selected for inclusion in this report. Annotations are provided in three primary categories: chromaticity and color perception, brightness perception, and LED airfield hardware; and are arranged alphabetically by author(s) and then by year of publication within each category.

<table>
<tr><td colspan="2">17. Key Words
Light-emitting diode, LED, Incandescent light, Airfield lighting, Airport lighting, Approach lighting system (ALS), Runway lighting, Taxiway lighting, Color vision</td><td colspan="3">18. Distribution Statement
Document is available to the public through the Internet: (http://www.faa.gov/go/oamtechreports/)</td></tr>
<tr><td>19. Security Classification (of this report)
Unclassified</td><td colspan="2">20. Security Classification (of this page)
Unclassified</td><td>21. No. of Pages
53</td><td>22. Price</td></tr>
</table>

Acknowledgments

The authors wish to acknowledge the assistance and collaboration of the research study sponsors and program manager for their feedback and guidance on the direction of this project. In particular, thank you to Matt Harmon, Mike Melssen, Janet Greenwood, and Dr. Chuck Perala. In addition, the authors are particularly grateful for the subject matter expertise and technical advice provided by Bryan Watson, Donald Lampkins, and Dr. Kevin Gildea. Finally, thank you to Janine King, Rebecca Didomenica, Terry King, and Mark Humphreys for their helpful feedback on earlier versions of this report.

This project is funded by the FAA NextGen Human Factors Division (ANG-C1) in support of the FAA Office of Aviation Safety (AVS), Flight Standards Service (AFS-400).

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List of Abbreviations

AC	Alternating Current
AFS-400	Flight Standards Service
AGL	Above Ground Level
ALS	Approach Lighting System
ANG-C1	Human Factors Division
AOA	Aerodrome Operators Association
ASRS	Aviation Safety Reporting System
AVS	Office of Aviation Safety
C	Celsius
CAA	Civil Aviation Authority
CCR	Constant Current Regulator
CCT	Correlated Color Temperature
cd	Candela
CIE	International Commission on Illumination
CVD	Color Vision Deficient
CVN	Color Vision Normal
DC	Direct Current
EFVS	Enhanced Flight Vision Systems
EISA	Energy Independence and Security Act
ERGL	Elevated Runway Guard Lights
EVS	Enhanced Vision Systems
FAA	Federal Aviation Administration
GFK	Grand Forks International Airport
HF	Human Factors
Hz	Hertz
ICAO	International Civil Aviation Organization
K	Kelvin
km	Kilometer
kt	Knot
LED	Light-Emitting Diode
LHR	Heathrow Airport, London
MAN	Manchester Airport
Mw	Milliwatt
MWIR	Midwave Infrared
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
nm	Nanometer
No.	Number
NVG	Night Vision Goggles

NVIS	Night Vision Imaging Systems
PAPI	Precision Approach Path Indicator
PHX	Phoenix Sky Harbor International Airport
PWM	Pulse Width Modulation
RPM	Revolutions Per Minute
SAE	Society of Automotive Engineers
sr	Steradian
SWIR	Shortwave Infrared
UK	United Kingdom
US	United States

Abstract

The primary objective of this report is to provide an overview of the available research literature on the use of light-emitting diodes (LEDs) for airfield lighting applications (e.g., runway, approach, taxi, apron lighting). These research efforts indicate several benefits of LEDs when compared to traditional incandescent or halogen lighting. LEDs tend to have a higher color saturation, which may provide a better opportunity to separate color boundaries and improve discriminability of airfield lights—this is particularly true during conditions such as fog or haze which tend to desaturate any light source color. LED-based approach lighting systems may be easier to detect at further distances, aiding in orienting a pilot to the runway environment sooner—particularly at nighttime or during reduced visibility conditions. LEDs have a much longer operating lifespan, which results in significant cost savings to airport operations budgets. As incandescent lamps become increasingly difficult to procure, switching to LED lighting ensures equipment and supplies are readily available to maintain airfield lighting infrastructure in the future. However, understanding how LED lighting may affect perceived brightness, perceived color, and compatibility with existing infrastructure and equipment are important safety considerations. Research indicates that LEDs may appear brighter than incandescent lighting, even when set to the same luminance levels—this is particularly a concern in certain weather conditions, such as fog. Although LED output can be adjusted to produce a brightness perceived to be similar to incandescent light sources, dimming LEDs may result in an undesired stroboscopic effect that is more likely to be experienced by pilots in single propeller aircraft. LEDs may not be compatible with certain flight deck vision technologies, such as Night Vision Imaging Systems (NVIS), Enhanced Flight Vision Systems (EFVS), or Enhanced Vision Systems (EVS), which may filter out and fail to display the wavelengths emitted by LEDs. Federal Aviation Administration (FAA) guidance materials have addressed many of the safety considerations identified in the research literature. Future research in the area of LED lighting for airfield applications is suggested, including the evaluation of additional environmental factors related to weather, and the inclusion of operationally relevant research designs. Thirty-nine references from 2001 to 2021 were selected for inclusion in this report. Annotations are provided in three primary categories: chromaticity and color perception, brightness perception, and LED airfield hardware; and are arranged alphabetically by author(s) and then by year of publication within each category.

Keywords: Light-emitting diode, LED, Incandescent light, Airfield lighting, Airport lighting, Approach lighting system (ALS), Runway lighting, Taxiway lighting, Color vision

Introduction

Airfield lighting provide visual cues on the ground to guide a pilot to a safe takeoff, landing, or ground maneuvering operation, and are particularly useful during nighttime or reduced visibility conditions. Because airfield lighting are required by some Federal Aviation Administration (FAA) operational rules, and contribute to improving both the safety and the capacity of operations (by enabling lower-visibility operations) at airports, they have been an area of focus for both safety-related research and technological advancement since the early days of aviation. For example, in the early 1900s, it was common to mark airfields using a burning haystack or oil-burning flares. Later, floodlights situated around the boundary of the airfield replaced the primitive lighting sources. Since the 1930s, incandescent lamps have been amongst the most common type of light sources used for airfield lighting, though other sources such as neon, argon gas, halogen, and cold cathode fluorescent lamps also have been used. In recent years, light-emitting diode (LED) lamps have become a viable option for airfield lighting applications, and as such, there is an increased interest in determining the human factors (HF), operations, and safety-related concerns for this lighting application.

Today, incandescent and halogen light sources are amongst the most common type of lights found on a modern airfield, and thus, those most likely to be replaced by LEDs. The implementation of LEDs for airfield lighting may have both advantages and disadvantages when compared to incandescent lamps, and it is important to understand these considerations as LED technology becomes increasingly common. The goal of this report was to gather and summarize the existing scientific research from the FAA and others on LED lighting as used for airfield applications (e.g., runway, approach, taxi, apron lighting). In addition, we provide policymakers, researchers, and others with an overview of this topic, as well as a reference list of relevant research and FAA guidance materials.

Background

When the Energy Independence and Security Act (EISA) of 2007 was signed into law, the United States (US) Federal Government set a plan to move toward energy independence, security, and increased efficiency. One of the provisions of the law (42 U.S.C. § 321) addressed lighting efficiency, with an aim of expanding the usage of alternative, energy-efficient lighting fixtures and bulbs. Unlike incandescent lighting, LED technology is able to produce more light without generating more heat, and the increased use of LEDs is consistent with the provisions of this law. As a result, the FAA has taken a phased approach to installing and evaluating new, more energy-efficient LED lighting for airfield applications in the US National Airspace System (NAS).

Any new technology may have both advantages and disadvantages, and LED lighting is no different. LED technology is more energy efficient, and the life-cycle costs for installation and maintenance of LED lighting systems for airfield applications are reduced when compared to the costs of installing and maintaining incandescent lamps. Beyond the economic benefits of LED lighting, incandescent lamps of certain wattages (and lumens) are likely to become difficult to procure as manufacturers change to LED technology. Together, these advantages result in significant savings in airport operations budgets and help to ensure equipment and supplies are readily available to maintain airfield lighting infrastructure in the future.

However, the FAA has a responsibility to ensure safe flight operations in the US NAS and must consider hardware reliability, the impact on flight operations, and HF concerns associated with LED lighting for airfield applications. For example, LEDs may not be visible with flight deck vision technologies, such as Night Vision Imaging Systems (NVIS), Enhanced Flight Vision Systems (EFVS), or Enhanced Vision Systems (EVS). As a result, certain flight operations, which would be supported by incandescent airfield lighting, may not be possible with LEDs. In some conditions, an operator may elect to avoid sections of the airfield that do not show in the NVIS. At certain settings, light fixtures that use pulse width modulation (PWM) to facilitate LED brightness changes may induce a stroboscopic (i.e., oscillating on and off) effect visible to pilots in single propeller aircraft (FAA Engineering Brief No. 67D). The appearance of this visual stroboscopic effect may be modulated by characteristics of the aircraft, such as the number of propeller blades, the distance between the leading edge to the trailing edge of each propeller blade, or the propeller revolutions per minute (RPM) setting (which would vary during a single approach to land operation). Further, incandescent lamps emit heat during operation, making them less energy efficient, but providing the benefit of melting any accumulating snow or ice. While LEDs emit some heat, an extra heater (i.e., Arctic Kit[1]) or other modifications may be required for airports that experience significant ice or snow.

To address some of the concerns about using LEDs for airfield lighting applications, FAA-sponsored research has included laboratory and simulator-based platforms to evaluate the properties of LED lights. The focus of this research has included topics such as perceived brightness (particularly during night operations), conspicuity in various weather conditions, color identification by pilots with and without color-deficient vision, flicker or stroboscopic effects, photometric measurements of light intensity over time, and LED system lifespan. While this list is not exhaustive, it does indicate some of the identified HF and engineering considerations associated with LED lighting for airfield applications.

As noted, the FAA is taking a phased approach to installing and evaluating LED lighting for airfield applications. This has allowed for field-testing over time, and the monitoring of pilot feedback during real-world variations in environmental lighting and weather conditions. A review of pilot reports that mention LEDs in the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS) suggest that the most frequently identified areas of concern relate to perceived brightness, undesired flickering or stroboscopic effects, and perceived double images (see Appendix D for examples from the ASRS database). Many of

[1] Federal Aviation Administration (2012).

these areas of concern have been evaluated through research and addressed in FAA guidance materials (see Table 1).

Table 1.
FAA Guidance Referencing LEDs

Document	Title	LED-specific Subsections
Advisory Circular No. AC 70/7460-1M	*Obstruction Marking and Lighting*	2.4. Light Failure Notification 11.4. Catenary Lighting Standards 13.8. Lighting of Wind Turbines During Construction Phase
Advisory Circular No. AC 150/5340-26C	*Maintenance of Airport Visual Aid Facilities*	4.1.5. Clamp-on Ammeter 5.3.2. Runway and Taxiway Elevated Edge Lighting Systems 5.4.2. Illuminated Runway and Taxiway Guidance Signs: Lamp Replacement 5.6.1. Lighted Wind Cone Assemblies: Preventive Maintenance Inspections 5.11.1. Obstruction Lights: Preventive Maintenance Inspection Procedures
Advisory Circular No. AC 150/5340-30J	*Design and Installation Details for Airports Visual Aids*	1.4. Mixing of Light Source Technologies 4.8.5. Taxiway Centerline Lighting and Clearance Bar Systems 11.5.4. Light Fixtures - General 11.5.7. Shielding Taxiway Lights
Advisory Circular No. AC 150/5345-43J	*Specification for Obstruction Lighting Equipment*	3.3.14.4. Alternative Light Source Equipment 3.4.1.1.1. Infrared Specifications for LED Obstruction Lights 4.2.2. Infrared Test for LED Obstruction Lights 4.2.3. Minimum IR Radiant Intensity
Advisory Circular No. AC 150/5345-46E	*Specification for Runway and Taxiway Light Fixtures*	
Advisory Circular No. AC 150/5345-53D	*Airport Lighting Equipment Certification Program*	5.c.v. Substitution of Light Sources Addendum [list of certified equipment and manufacturers]
Engineering Brief No. 67D	*Light Sources other than Incandescent and Xenon for Airport and Obstruction Lighting Fixtures*	III. Background VII. Applicable Documents VIII. Principal Changes
Engineering Brief No. 98	*Infrared Specifications for Aviation Obstruction Light Compatibility with Night Vision Goggles (NVGs)*	
Information for Operators No. InFO 11004	*Enhanced Flight Vision System (EFVS), Enhanced Vision Systems (EVS), and Night Vision Goggles (NVG) Compatibility with Light-Emitting Diodes (LEDs) at Airports and on Obstacles*	
Safety Alert for Operators No. SAFO 09007	*Night Vision Goggle (NVG) Advisory Pertaining to Certain Red Color Light Emitting Diodes (LED)*	

Method

This report summarizes and synthesizes the available literature on the use of LED lighting for airfield applications. In general, this research has focused on the impact of LEDs on visual perception, comprehension, hardware system reliability, and the safety of flight operations in the US NAS. Literature annotated in this report includes airfield lighting-related FAA technical reports, airfield lighting guidelines, peer-reviewed journal articles, conference proceedings and presentations, and unpublished author manuscripts. Literature were collected from aviation transportation authority websites, conference websites, Google Scholar, and other search databases using combinations of the following keywords and/or phrases:

- [LED | light emitting diode] & [aviation | aerospace | airfield | airport | runway | approach light | taxi]
- [airfield | runway | airport | taxi | taxiway] & lighting

Inclusion Criteria

Thirty-nine references met the criteria for inclusion in this report based on relevance to the topic (i.e., discusses LEDs in the context of airfield lighting; see Table 2).

Table 2.
Literature Selected for Annotation

Literature Type	Count
Technical Report	13
Journal Article (Peer Reviewed)	8
Conference Proceeding or Presentation	12
Unpublished Manuscript	5
Product Technical Brief	1
TOTAL	**39**

Prior to 2001, incandescent (and halogen incandescent) light sources were primarily used in airfield applications; therefore, the literature on LED applications in airfield lighting are recent with publication dates ranging from 2001 to 2021. This report organizes the literature into three categories: chromaticity and color perception (Appendix A), brightness perception (Appendix B), and LED airfield hardware (Appendix C). In cases when the subject matter of a reference overlapped across categories, the annotation was added only to the most relevant category.

Findings

Approach lighting systems (ALSs) help orient the pilot to the runway environment, and provide the bridge for the transition from instrument flight to a visual see-to-land operation.[2] When used for ALS applications, one benefit of LEDs is that they may be distinguishable by pilots at farther distances when compared with their incandescent counterparts.[3] Earlier orientation to the runway environment, particularly during reduced visibility conditions such as fog, rain, snow, or even nighttime, may be an enhanced safety feature of LED lighting. However, the flashing of colored LEDs may affect perceived brightness, which can differ from objective measures of brightness, particularly during onset and offset (i.e., the moment LEDs switch on and off).[4] Additionally, caution is recommended when using LEDs in low visibility weather conditions, as fog has been found to affect perceived brightness due to light refraction.[5] LED output can be adjusted to a brightness level perceived by observers to be similar to incandescent light sources; however, dimming LEDs can result in undesired stroboscopic effects.[6] As mentioned previously, pilots of single propeller aircraft are the most susceptible to experiencing a visual stroboscopic effect at certain LED settings (FAA Engineering Brief No. 67D).

In addition to differences in perceived brightness, LEDs produce light in a narrower wavelength, which may affect the perceived color. As the use of LEDs for airfield lighting applications increases, it is important to ensure that they can be adequately identified by pilots who are color vision normal (CVN), but also those with color vision deficiencies (CVDs). FAA-sponsored research has demonstrated that both individuals who are CVN and who are CVD (in this case, protan and deutan) were more accurate at identifying green and white LED signal lights compared to incandescent lights.[7,8] As an example, color identification accuracy of the color green increased from 60% to 80% for protan participants, and 65% to 85% for deutan participants when using an LED signal (compared to an incandescent signal). Additionally, for CVN individuals, there were no differences in color identification for yellow, blue, or red LED and incandescent lights. However, for other colors (particularly yellow), CVD participants performed worse at color identification with LED lights than with incandescent lights. Color identification accuracy of the color yellow decreased from 60% to 40% for protan participants,

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[2] Fercho (2021); see Bridgers and Richards (1974) for a discussion on the theory and practice of airfield lighting.
[3] Snyder et al. (2021).
[4] A review of NASA ASRS suggests pilot comments about the brightness of LED airfield lighting are consistent with findings identified in the literature and described in this report.
[5] Bullough (2014a); Bullough (2014b).
[6] See Bullough et al. (2014) for a discussion of stroboscopic and other effects.
[7] Bullough (2014a); Bullough (2014b).
[8] Due to the layout of the human visual system, there are three main types of CVD, protanopia/protanomaly, deuteranopia/deuteranomaly, and tritanopia/tritanomaly, each corresponding to a disorder of one of the three color-photoreceptor types in the eye. Individuals who have CVD are not necessarily missing an entire type of photoreceptor (as in protanopia, deuteranopia, or tritanopia), but may perceive shifted color sensitivities compared to CVN (as in protanomaly, deuteranomaly, or tritanomaly). These shifted sensitivities among individuals with CVD are of particular concern when assigning operational meaning and importance to colored lights on the airfield.

and 80% to 65% for deutan participants when using an LED signal (compared to an incandescent signal). Overall, the higher color saturation of colored LEDs (versus incandescent light sources) results in a net benefit for aviation signal light color identification for pilots, most of whom are CVN.[9,10] This color identification benefit associated with increased color saturation is particularly helpful during conditions of fog or haze, which tends to desaturate any light source color. It is important to note that the ranges of chromaticities allowed means that LEDs provided by different LED manufacturers may vary (FAA Engineering Brief No. 67D). Additionally, the chromaticity of a set of lights can drift as lenses age and discolor over time, so that the perceived color of a newly installed light may differ from one that is substantially older. In the future, research with CVD participants should consider these operationally relevant aspects of LED lighting.

The visibility of LEDs on the airfield or the use of red LEDs for obstruction lights is a particular concern to pilots using NVIS, EFVS, or EVS.[11] EVS supplements human vision with additional scene information during conditions of reduced visibility, obscuring media (e.g., clouds, dense fog), or at nighttime. NVIS function by amplifying ambient light, and aid the pilot's ability to maintain visual surface reference at night. If a vision system is designed to detect point source heat, LEDs may not produce sufficient heat for detection, thereby potentially increasing the risk associated with the operation. This could result in a situation where pilots using these technologies may not see LEDs on an airfield or red obstruction lights.

In the short-term, switching to LEDs carries high up-front costs associated with fixture and power supply replacement, and potentially heating circuits.[12] For example, LED systems can generate electrical interference with other equipment, which will require resources to implement compatibility testing.[13] In many cases, traditional incandescent light sources emit enough heat to melt accumulating ice and snow, but LEDs may not unless they are installed in enclosures designed to either generate heat (e.g., via an "Arctic Kit" with an added heater circuit) or draw and transfer heat from the LED to the outside of the lighting fixture.[14] Industry has been responding to problems in colder climates where airports have experienced icing and snow accumulation on LED light fixtures.[15]

In the long-term, switching from incandescent airfield lighting to LED lighting is cost-effective, as LEDs have a much longer operating lifespan than incandescent light sources.[16] However, LEDs may fall below the threshold of discriminability by the human eye by dimming to unacceptably low brightness levels over time. In contrast, incandescent light sources tend to

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9 Aviation signal light colors may be red, white, yellow, blue, or green.
10 Bullough et al. (2012).
11 Johnson and Dermody (2015).
12 Lean et al. (2010); Bullough (2012).
13 Cyrus (2005); see also Petrick (2002).
14 Gu et al. (2007); Marsh et al. (2008); Kopp Glass (2011).
15 Marsh et al. (2008).
16 Narendran and Freyssinier (2014).

fail instantaneously (i.e., failure means no light is emitted at all).[17] In addition, while testing shows early support for LEDs embedded in airfield surfaces, such as at taxiways and aprons, hardware longevity is a concern for situations where aircraft tires are expected to roll over embedded fixtures.[18] These differences in operating lifespans and failure conditions suggest that existing lighting infrastructure maintenance procedures will need to be revised to accommodate the characteristics of LEDs. Tools to help calculate a cost analysis for airfield LEDs (and other light sources) are available.[19] Overall, it will be important for the individual airfield to consider upfront cost and the savings associated with LEDs when deciding to convert to LED lighting; however, as incandescent hardware becomes more expensive and difficult to procure, these LEDs will become more widely used.

Discussion and Future Directions

Research undertaken by the FAA and others has resulted in an increased knowledge of LED properties for airfield lighting applications. These properties can be split into three categories: chromaticity and color perception, brightness perception, and LED airfield hardware.

Chromaticity and Color Perception

Research sponsored by the FAA has demonstrated that the increased color saturation of white and green LEDs may result in improved color identification by both CVN and CVD pilots. Further, results from this research suggest that there are no appreciable color identification performance deficits when comparing other LED colors for CVN participants. However, it was observed that individuals with CVD may encounter difficulties when identifying yellow, blue, or red LEDs (though this is true with incandescent lighting as well). Based on the results of this research, the FAA revised its chromaticity requirements for aviation signal lights using nonincandescent light sources, such as LEDs. These revised requirements are outlined in Engineering Brief No. 67D. Future research should consider operational aspects that may affect color perception for both CVN and CVD pilots, such as the wide ranges of chromaticities allowed for LED lighting and the effects of the longer LED life cycle on lens age and discoloration.

Another real-world consideration is the effect that LEDs may have on pilot perception and comprehension during higher workload tasks, such as low-visibility approach to land operations; the perception and comprehension of airfield lighting may differ from what would be observed in a less demanding context. Additionally, color identification of LEDs or the ability to detect obstacles (e.g., vehicles, obstacles, animals, people) on a runway may be affected when viewing a cluttered airfield environment, particularly if that airfield includes a combination of

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[17] Lean et al. (2010).
[18] Gallagher (2005); Wang et al. (2010).
[19] Chao et al. (2021).

both incandescent and LED lighting systems, under conditions of obscuring media (e.g., fog), and with time pressure.

Brightness Perception

The perceived brightness of LEDs is of particular concern for safe airfield use,[20] and models, such as the Blondel-Rey model, can help narrow the range of colors and brightness of LEDs to be tested.[21] However, the use of models cannot replace laboratory experiments or field-tests entirely, which will require representative human test participants (e.g., pilots, air traffic controllers) in realistic operational testing scenarios.

Differences in the perception and comprehension of airfield lighting under varying ambient lighting and weather conditions, and during different types of operations (e.g., visual vs. instrument flight rules) must be considered. For example, fog may affect the perception of LED brightness and chromaticity,[22] but the relationship between LED perception and fog density/droplet size requires further evaluation. This is an admittedly difficult phenomenon to study, as even the most advanced flight simulation visual systems are unable to model properties of lighting or weather conditions exactly replicating real-world environments. Further, it is challenging and risky to schedule flight tests during actual weather conditions. As research into the area of LED use for airfield applications continues, it is important that testing methodologies be directly applicable to real-world aviation applications. It is difficult for models to account for observed differences in perception during different conditions (e.g., fog density) or account for individual variations in human perception.

Further considerations not well represented in the literature include the effect of LED lighting on the safety of flight operations during conditions often associated with optical illusions. For example, flat light[23] can impair a pilot's ability to perceive depth or distance, even when operating under visual flight rules. During operations in flat light or whiteout conditions, the brightness of LED lights may need to be adjusted for pilots to maintain visual reference with the ground during takeoff and landing operations. This is particularly important if other sources of visual guidance, such as approach slope indicators for approach operations, are not present.

LED Airfield Hardware

Implementing LED hardware in the airfield environment cannot be completed without some consideration of the required resources. Converting an airfield from incandescent lights to LEDs is accompanied by high initial cost; conversely, the initial cost can be offset over the lifetime of the LED lighting system through lower operating costs. Specifically, lower operation costs can be achieved through reduced energy consumption, longer hardware lifecycles, and less

[20] See Appendix B for annotations; see Appendix D for ASRS excerpts.
[21] Milburn et al. (2013); Yakopcic et al. (2013).
[22] Bullough (2014a, 2017); Bullough et al. (2015); Kurniawan et al. (2007); Snyder et al. (2021).
[23] i.e., light that produces minimal contrast between highlights and shadows.

expensive/readily available replacement parts.[24] Each airfield should use a cost analysis to inform an action plan for the individual airfield and desired LED lighting equipment.

Outside of the HF issues outlined in earlier sections of this report, there are additional concerns associated with the use of LED hardware. As previously mentioned, LEDs may not produce enough natural heat to melt ice and snow from accumulating around the lighting fixture. This lack of heat also makes LEDs incompatible with some flight deck vision systems. Lastly, one of the more concerning issues relates to failure detection. While incandescent lights experience a complete failure when they reach the end of their lifecycle, LEDs tend to become slowly less bright over time until a failure. This would require a standard maintenance schedule to check the brightness of each fixture to ensure the luminance level has not decayed below a standard threshold.

This report intends to provide an overview of available literature on the topic of LED lighting for airfield applications. Brief discussions of the salient points of each article or report are provided in the annotations section of this report. It is important to note that many of the findings outlined in the annotations have been addressed in FAA guidance (see Table 1). However, additional research to address new questions that will arise as LEDs enter service in airfield lighting applications is recommended.

[24] Chao et al. (2021).

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Appendix A

Chromaticity and Color Perception Annotations

Bullough, J. D. (2014a). *Can LEDs Be Seen in Fog as Well as Incandescent Lamps* (Report No. S10101) [Paper presentation]. 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, N. J., August 4-8, 2014. https://www.airporttech.tc.faa.gov/Collaboration/Past-Conferences-Events/Airport-Technology-Transfer-Conference-2014/PgrID/4468/PageID/1

Using LEDs for airfield applications have some advantages, such as reduction in energy consumption and increased accuracy in color identification. Before using LEDs as an airfield lighting source, it is important to understand how these lights are perceived in low ceiling or foggy conditions. Color identification is usually better for LED light sources than incandescent lighting, especially for the color green. White color LEDs are less often mistaken as yellow compared to white incandescent lights. Fog affects the chromaticity attributes of colored lights. For example, the scattering of short wavelength light, such as green, will make the color appear more yellow—but with LED lighting, this shift is less noticeable due to the narrow spectral distribution of light produced by LEDs. Low ceiling or foggy conditions may reduce the advantages of LEDs in color identification, especially in daytime conditions. However, fog does not affect detecting the onset of flashing lights, and fog should not affect LED lighting any more than incandescent lights.

Bullough, J. D. (2014b). *Matching LED and Incandescent Aviation Signal Brightness* (Report No. S10103) [Paper presentation]. 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, N. J., August 4-8, 2014. https://www.airporttech.tc.faa.gov/Collaboration/Past-Conferences-Events/Airport-Technology-Transfer-Conference-2014/PgrID/4468/PageID/1

Occasionally, pilots have reported that LED runway lights appear brighter than their incandescent counterparts. High color saturation produced by LED lights is often perceived as brighter than incandescent lights, even when the two light sources are at the same illuminance intensity. At the direction of the FAA, the Lighting Research Center at Rensselaer Polytechnic Institute developed a brightness correction factor for LED lights. Comparing white incandescent light to an LED near 6700 Kelvin (K), the brightness intensity can be reduced to 67% of the incandescent light and retain equal perceived brightness intensity. With a white LED near 3300 K, the intensity could be reduced to 83% to obtain the same perceived brightness intensity. Blue LED sources could be reduced to 72% of brightness intensity. A green LED source with a wavelength of 525 nanometers (nm) can be reduced to 72% and 61% for a wavelength of 505 nm. Red and yellow lights are perceived as similar in brightness, whether from an LED or an incandescent source; thus, no adjustment is expected to be required for these colors. Viewing in fog, white light near 6100 K must be reduced to 74% of incandescent brightness intensity whereas white lights near 3300 K must be reduced to 88%. Blue and green light must be reduced to 86% of brightness intensity. The study was conducted using a single light source in simulated fog rather than multiple light sources in environmental fog, so real-world applications may differ from these results.

Bullough, J. D. (2017). Human factors impacts of light-emitting diode airfield lighting. *Transportation Research Record*, *2626*(1), 51-57. https://doi.org/10.3141/2626-07

LEDs have recently been considered for runway and taxiway lighting in lieu of traditional incandescent light sources. LEDs have longer service cycles, require less maintenance, and are more energy efficient than incandescent lights. However, LEDs are often perceived to be brighter than incandescent light sources at equal illuminant levels. This effect may be less noticeable when the LED brightness is about 60% of incandescent light sources. Fog refracts the light similarly in both incandescent and LED lighting. Due to the difference in perception between incandescent and LED light, HF should be considered when using both light sources on the same airfield.

The perceived color of LED and incandescent light sources also differs, potentially altering the perception of airfield lighting. The narrow band of light wavelengths that LEDs emit result in the appearance of highly saturated color without using filters often applied to incandescent lights. To test the difference between produced colors from the different light sources, 50 participants viewed and classified the color of LED and incandescent lights. Of these, 29 were CVN, 8 were protanomalous[1] CVD, and 13 were deuteranomalous[2] CVD. CVN observers were more accurate with white and green LEDs than with incandescent lights; participants misidentified white light as yellow when viewing incandescent lighting about 5% of the time. The same trends appeared for the CVD observers. However, for other colors, the CVD group was more accurate with incandescent lights.

[25] i.e., red-green color blindness where the eyes' cone photoreceptors are not sensitive enough to red and are too sensitive to green

[26] i.e., red-green color blindness where the eye's cone photoreceptors are not sensitive enough to green but are too sensitive to red

Bullough, J. D., & Liu, Y. W. (2019). Response to white light emitting diode aviation signal lights varying in correlated color temperature. *Transportation Research Record*, *2673*(3), 667-675. https://doi.org/10.1177%2F0361198119834007

Chromaticity describes the hue (color parameters) and saturation (color intensity) of a light source but does not describe brightness. It is important to understand the chromaticity attributional difference between incandescent and LED lighting before applying LEDs to an airfield application. An attribute of incandescent lighting is the shift in chromaticity with brightness. The FAA regulates the parameters of chromaticity for airfield lighting, but these parameters should be re-evaluated for non-incandescent light sources.

Reports have indicated that people perceive LED lights to be brighter even when lit at the same luminous intensity. Three studies were conducted to evaluate brightness, discomfort in dark conditions, and peripheral detection. The brightness study used a 2700 K LED and a 5900 K Correlated Color Temperature (CCT) LED, where participants judged which light was brighter when presented at the same time. In the second experiment, participants subjectively reported on their discomfort towards the lights. The third experiment considered nighttime peripheral detection by presenting LED lights at an intensity equivalent to viewing a 5,000-Candela (cd) light at 2.5 kilometers (km); no practical differences were found between the 2700 K and 5900 K LEDs. The results are in line with published predictive models. Thus, using these models can correct for brightness in non-incandescent light sources while retaining chromaticity values. The peripheral-vision results suggest no great advantage in rod receptor stimulating light sources.

Bullough, J. D., & Skinner, N. P. (2014a). Do LEDs Increase the Accuracy of LED Aviation Signal Light Color Identification by Pilots with and without Color-Deficient Vision? (Report No. S10104) [Paper presentation]. 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, N. J., August 4-8, 2014. https://www.airporttech.tc.faa.gov/Collaboration/Past-Conferences-Events/Airport-Technology-Transfer-Conference-2014/PgrID/4468/PageID/1

LED lighting is being considered for airfield light sources due to maintenance, energy benefits, increased color saturation, and CCT for white light. Color parameters for lighting guidelines used by the FAA were advised by the Society of Automotive Engineers (SAE) several decades ago and have not been revised or updated, and thus may need to be revised for LED lighting sources. Some illumination properties, such as brightness and color, may need adjustments for LED airfield applications. Specific chromaticity requirements are set for white, yellow, green, red, and blue colored lights; however, CVD pilots may have more difficulty in identifying specific colors.

The high color saturation of LED light sources reduces the likelihood of a CVN observer mistaking a color for white. Conversely, a CVD pilot may use different cues for color identification. As a check, CVD pilots observing an incandescent light source (incandescent lights use coverings to produce different colors) may use the brightness level to confirm the distinction between red and white, as the red would be perceived as dimmer. This mechanism would not be useful with LED lighting sources. A laboratory study compared incandescent lighting, LED lighting set to mimic incandescent lights, and LED with equal input power. The study recruited 29 CVN participants, 8 protan CVD participants (red-green color blindness; cones are less sensitive to red wavelength and hypersensitive to green), 13 deutan CVD participants (red-green color blindness; cones are less sensitive to green wavelength but hypersensitive to red).

CVN participants were more accurate at identifying green, white, and blue with an LED light source compared to the incandescent light source. There was no observed difference between LED incandescent-mimicking and equal nominal input power conditions. Protan CVD participants identified white and green LED light sources better than incandescent light sources, but were worse at identifying yellow, blue, and red LEDs. Protan CVD participants identified green better in the LED incandescent-mimicking condition. Deutan CVD participants identified LED signals for green and white better than the incandescent light source. Deutan CVD participants identified the color blue better in the incandescent-mimicking condition than in the equal nominal input power condition. Protan CVD participants identified yellow with less accuracy when next to a green LED light source. The study provides support that CVN observers are often more accurate at color identification for LED light sources; however, chromaticity requirements may need to be reconsidered for LED lighting, especially with pilots who are CVD.

Bullough, J. D., Skinner, N. P., Bierman, A., Milburn, N. J., Taranta, R. T., Narendran, N., & Gallagher, D. W. (2012). *Nonincandescent Source Aviation Signal Light Colors* (Report No. DOT/FAA/TC-TN12/45). U. S. Department of Transportation, Federal Aviation Administration. https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/54/Nonincandescent-Source-Aviation-Signal-Light-Colors

Incandescent and LED lights have different chromaticities, which may impact correct color identification. Color-filtered and unfiltered incandescent and LED lights, need to be compared to determine the chromatic regions of the International Commission on Illumination (CIE) color space that are most likely to be identified correctly (while minimizing confusion with other colors). For example, several shades of “white” colors were shown to participants, who were asked to name the color. The researchers then identified the shade of “white” that was associated with the highest agreement and least confusion among participants.

In the first experiment, participants were shown an airport runway model lit with different shades of white, yellow, red, blue, or green, and were asked to name the displayed color. The procedure was repeated with colors generated either by liquid-crystal display (LCD), or with a selection of LEDs and color filters (used to shift chromaticity). Again, researchers then identified the shade for each color that received the highest agreement (and least confusion) among the participants. When extrapolated according to the CIE colorspace, researchers concluded that blue chromaticities were less likely to be confused for “white” than yellow chromaticities. These results indicate that current chromaticity boundaries for “white” lights in aviation may need to be reconsidered.

The second experiment was conducted with CVN and CVD participants who were more likely to demonstrate color confusion. Participants observed white, yellow, red, blue (cyan), or green lights, and were asked to name the color they saw. The colors were produced using 35-watt incandescent lights behind a screen fitted with a pinhole and a color filter, or with LEDs behind pinholes. In general, LEDs resulted in higher identification accuracy from CVN participants. Protan CVD participants were better at LED color identification for green and white but worse with LEDs for yellow, blue, and red. Deutan CVD participants were better at LED identification for green and white, worse for yellow and blue, but no different between LED and incandescent lights for red. These results suggest that performance may be due to a higher saturation of colors than equivalent incandescent lamps, blue LEDs support better color identification than green LEDs, and yellow LED identification may be improved by modifying boundaries.

The third experiment tested aviation lights within FAA-defined color boundaries. As before, LEDs and 35-watt incandescent lamps (which were placed behind screens fitted with pinholes), were observed by CVN participants in a darkened room. Based on the results, Bullough et al. suggested that boundaries for yellow are problematic, and should be reconsidered. Recommended boundaries for colors (in the CIE colorspace) to reduce confusion among airfield LED lights were provided.

Bullough, J. D., Yuan, Z., Rea, M. S., & Gallagher, D. W. (2015). *Brightness/Luminous Intensity Values for Blue, White, and Green Aviation Signal Lights using Light-Emitting Diodes* (Report No. DOT/FAA/TC-TN15/32). U. S. Department of Transportation, Federal Aviation Administration. https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/30/BrightnessLuminous-Intensity-Values-for-Blue-White-and-Green-Aviation-Signal-Lights-Using-Light-Emitting-Diodes

Pilot reports have suggested that LEDs used as signal lights around airports and on the ground are perceived as brighter than their incandescent counterparts. LEDs tend to produce more saturated colors compared to incandescent bulbs, and this characteristic of LEDs may correspond to their increased perceived brightness compared to incandescent sources. It was hypothesized pilots would find LEDs to be more distracting or disorienting than incandescent sources. Across four experiments, incandescent and LED lights were compared under singular bulb, arrays of bulbs, dim, dark, and simulated fog conditions. Based on these results, LED signal lights were perceived as brighter than incandescent signal lights at matched luminance intensities.

Fog refracts and desaturates the (intensity-matched) light output from LEDs and incandescent light sources in a way that eliminates any differences in perceived brightness. A new model was created that could be used to predict signal light perceived brightness for FAA blue, white, and green colors. This model was able to predict brightness perception for this study, and other previously published studies. However, this new model failed to predict the effect that particularly short-wavelength blue lights had on brightness. Rather, chromaticity contributed to the brightness of LEDs perceived by pilots regardless of their luminosity. Future studies involving highly saturated blue signal lights should be conducted to explain this result.

Kurniawan, B. A., Nakashima, Y., Takamatsu, M., & Kidoh, Y. (2007). Visual perception of color LED light in dense fog. *Journal of Light & Visual Environment*, *31*(3), 152-154. https://doi.org/10.2150/jlve.31.152

Fog scatters light in all directions, which can reasonably be expected to reduce visibility. The goal of the research was to determine how much loss of visibility occurs in foggy conditions when observing LED sources. Fog was simulated by a fog generator that emitted into a sealed case. The case was fitted with two clear panels to allow a viewer to see through the fog within to LEDs mounted on the other side. 10 µm- and 50 µm-sized droplets were used at six different droplet densities. Participants were asked to rate the brightness of red, green, yellow, and blue colored lights in fog on a 10-point scale relative to white light observed without fog. Perceived brightness varied by color, with blue light showing the greatest decrease in perceived brightness. In general, the results suggest that all lights that had a blue component were associated with a decrease in reported brightness. Although this was not a test to study aviation lighting, the methods and equipment may be adapted to simulate foggy environments that may be found on airfields.

Milburn, N. J., Gildea, K. M., Bullough, J. D., & Yakopcic, C. (2013). Aviation-related light-emitting diode (LED) perception research. *Aviation, Space, and Environmental Medicine*, *84*(8), 876-878. https://doi.org/10.3357/ASEM.3774.2013

There may be several advantages to using LEDs over traditional incandescent lights in airfield lighting applications. Besides the increased efficiency of LED lights, there are additional HF advantages over traditional incandescent lights. Incandescent lights, when dimmed, can produce a yellowish-white color. However, certain blue LEDs can be down-converted to yellow light when coated with phosphors, and this can result in the light being perceived as white with a slightly bluer tint.

Color identification was evaluated with CVN and CVD participants. Using an LED light source increased correct color identification for CVN participants, especially for white and green colors. CVD participants identified white and green lights better than they identified yellow, blue, and red. When intensity between LED and incandescent light sources were matched, protan[3] CVD participants had better identification of green LEDs, and deutan[4] CVD participants had better identification of blue LEDs. When the colored LED was paired with red, protan CVD participants were more likely to identify yellow incandescent light sources as green rather than red. When paired with green, protans had lower identification of yellow LEDs, but higher identification for green LEDs.

Further studies did not find heterochromatic groupings provided any benefit, regardless of color-vision ability. A consideration when using LEDs for navigational lighting is that when LEDs are flashed, they produce a different perceived brightness intensity profile than when incandescent lights are flashed. Four models were evaluated to understand which would provide the best model for estimating LED intensity (Allard, Modified Allard, Blondel-Rey, and Douglas). The Blondel-Rey model was the most conservative, but the Modified Allard and Allard models may be more appropriate for establishing a threshold for LED light sources.

Milburn, N. J., Gildea, K. M., Perry, D. L., Roberts, C. A., & Peterson, L. M. (2014). *Usability of Light-Emitting Diodes in Precision Approach Path Indicator Systems by Individuals With Marginal Color Vision* (Report No. DOT/FAA/AM-14/6). U. S. Department of Transportation, Federal Aviation Administration. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201406.pdf

In anticipation of the rollout of LEDs to replace incandescent lights in Precision Approach Path Indicator (PAPI) systems, an experiment was conducted with CVN and with CVD participants (protans, deutans, tritans)[5]. Individuals who are both red-green and yellow-blue deficient were included. Participants were presented with red and white light configurations in a PAPI simulation with either incandescent or LED lights and were asked to identify the colors of the 4-light simulated PAPI instrument. Results were not significantly different between incandescent and LED conditions. Participants who were both red-green and yellow-blue deficient performed significantly worse than all other color vision groups. The results of the other groups were not significantly different, suggesting that pilots with color vision waivers will perform as well with red and white LED PAPI systems as with incandescent PAPI

[27] Protan CVD is a red-green color blindness in which affected individuals have abnormal (protanomalous) or missing (protanopic) red cone receptors.
[28] Deutan CVD is a red-green color blindness in which affected individuals have abnormal (deuteranomalous) or missing (deuteranopic) green cone receptors.
[29] Tritan CVD is a blue-yellow color blindness in which affected individuals have abnormal (tritanomalous) or missing (tritanopic) blue cone receptors.

Appendix B

Brightness Perception Annotations

AOA Technical Working Group. (2012). *Evaluation of LED High Intensity Runway Centreline Lights Evaluation Report* (No. DIO/PTS/26/5/5/10) [Unpublished manuscript].

An evaluation trial for high-intensity LED runway centerline lighting at Manchester Airport (MAN), Manchester, United Kingdom (UK), was commissioned by the Aerodrome Operators Association (AOA) Technology Working Group and supported by the Civil Aviation Authority (CAA). This evaluation follows a previous trial in which low-intensity LEDs were evaluated at Heathrow Airport (LHR), London, UK, and found to be acceptable for taxiways. The evaluation at MAN was to determine if LEDs could be used as a light source in high-intensity runway light units.

The evaluation was conducted in two phases. In Phase 1, 27 centerline LED lights were installed in the first 1000m of runway 23L at MAN and either showed white for runway 23L or a combination of red and white for runway 05R. In Phase 2, 204 LED light units and touch down zone services (120 LED light units per end) were installed on runway 23R/05L on the complete runway centerline at MAN.

In Phase 1, photometric measurements were taken on a weekly basis over three months. The intensity of the white LED lights measured at maximum intensity was less than that of the replaced incandescent lamps, but the measured intensity of the red LED lights was greater than those from the removed incandescent light units. When both sides of the runway centerline light unit were illuminated, the intensity of the white LED lights increased to be closer to, yet still below, the minimum average intensity required. LED light units were found to have an increased consistency of performance compared to incandescent lamps, which was attributed to large tolerances in luminous flux of the incandescent lamps and the vulnerability of incandescent lamp filaments to physical degradation. There was a noticeable visual difference in color between white LED and incandescent lamp units, especially when the intensity of the centerline lights was reduced. As intensity was reduced, incandescent lamps appeared more yellow while LED lights remained white in appearance. There were no reported instances of pilots being affected by glare from the LED light units, though it is unclear how pilots were surveyed.

The findings from Phase 2 support those identified in Phase 1. In Phase 2, 60 pilots were surveyed and 86% of respondents indicated that the clarity and color definition of the LED light units were excellent, and 80% preferred LED lights to incandescent lights. In reviewing pilot feedback, comments related to HF concerns included that, (a) LED lights appear brighter than incandescent lights, especially when closer to the ground or at night in wet conditions; (b) a flicker effect was detected; and (c) LED lights had a blue tone.

Bullough, J. D., & Skinner, N. P. (2014b). *Can Linear Light Sources be Beneficial to Pilots?* [Paper presentation]. 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, N. J., August 4-8, 2014. http://www.airporttech.tc.faa.gov/DesktopModules/FlexNews/DownloadHandler.ashx?id=3d4fb4f6-09cc-469c-8364-3b40253fcc28&f=S10108-Bullough_Skinner.pdf

Airfields are delineated using individual light fixtures. Here, research was conducted to determine if there may be a benefit to using continuous lights, compared to discrete individual light fixtures. Previous research suggests that linear elements may provide a better understanding of orientation and increase confidence.

In Experiment 1, blue taxiway edge lights were tested in a computer simulation as individual lights (tested with 25, 50, 100, or 200 feet spacing) or as continuous delineation. Participants were asked to respond with the type of taxiway intersection that was being displayed (cross, tee, skew left, skew right). Results indicated a statistically significant advantage to spacing lights closer than 200 feet apart.

Experiment 2 examined the effect of turns that were either perpendicular or 30-degree skewed, with linear elements that were 2, 8, or 32 feet long and 50, 100, or 200 feet apart on reaction times. Results indicated that the shortest elements (2 feet) at the longest distances (200 feet) resulted in the longest reaction times. The longest elements (32 feet) and the shortest distances (50 feet) resulted in the shortest reaction times. The analysis also suggested that the shortest linear elements (2 feet) were effectively equivalent to individual lights (point sources) in terms of reaction times.

Experiment 3 repeated Experiment 2, but with added background noise (i.e., unrelated random line segments presented in the simulation). The background noise increased reaction times, but did not affect the relationship between length and distance found in Experiment 2.

Experiment 4 added the element of motion to the simulation, and Experiment 5 added a neutral density filter to reduce the luminance of the simulations presented in Experiment 4. The results of Experiment 4 were correlated with the results of Experiment 2, albeit with much longer reaction times.

The results of Experiment 5 were moderately correlated with the results of Experiment 2, albeit with much longer reaction times.

Experiment 6 was conducted in a darkened room with LEDs instead of computer screen simulation. The results were moderately correlated with the results of Experiment 2.

Overall, results were consistent and identified a relationship between light length and light spacing. The simulation results suggested that linear lights delineating taxiways are associated with shorter reaction times, compared to individual lights. Real-world testing is recommended.

Bullough, J. D., Skinner, N. P., Chambers, N., Young, S., Freyssinier, J. P., Narendran, N., Gallagher, D. W. (2017). *Effectiveness of Linear Elements for Taxiway and Runway Delineation* (Report No. DOT/FAA/TC-TN17/38). U. S. Department of Transportation, Federal Aviation Administration. https://www.tc.faa.gov/its/worldpac/techrpt/tctn17-38.pdf

Based on research investigating linear delineation for roadway applications, linear delineation elements may provide better information to pilots for taxiway and runway boundaries than source light fixtures. Blue taxiway lights are an example of a point source light fixture, where a series of fixtures provides a "dotted line" delineation of a taxiway. A linear delineation element would be as if a solid line, such as a paint stripe, glowed as a whole. The current report discusses three studies—laboratory, flight simulator, and field—considering delineation for aviation applications. Using LEDs for such applications has been previously considered; a prior study found that using LEDs for such applications may increase visual acquisition. However, installing LEDs in such a configuration may be difficult and may not give the visual perception of continuous light if not properly installed.

The laboratory study used a laptop computer screen and recorded participant responses. Participants viewed various types of light spacing (0, 25, 100, and 200 feet) and different runway cross-sections. Continuous lighting resulted in shorter response times to identify the type of cross-section.

Similar results were found in the simulator study; pilots in an Airbus A320 simulator environment were able to identify the type of cross section at a farther distance when light spacing was reduced.

The field study utilized green LED sources in a section that could operate as 2, 4, 8, or 16-foot sections. Participants viewed different combinations of linear LED lights while taxiing at an airport. Visual acquisition times and determination accuracy based on lighting spacing or length were measured. The best spacing for lights was approximately 16 feet linear LED light lengths and there was a clear benefit over traditional point lights or shorter light lengths.

Bullough, J. D., Tan, J., Narendran, N., & Freyssinier, J. P. (2014). *Understanding Flicker in Airfield Lighting Applications* (Report No. S10107) [Paper presentation]. 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, N. J., August 4-8, 2014. https://www.airporttech.tc.faa.gov/Collaboration/Past-Conferences-Events/Airport-Technology-Transfer-Conference-2014/PgrID/4468/PageID/1

All light sources can produce a flicker known as the stroboscopic effect. Understanding the HF components of this effect in airfield lighting applications can help influence design regulations. The stroboscopic effect may be caused by waving an object back and forth under a strobing light. This creates the perception of seeing several images, known specifically as the Wagon Wheel Effect. A similar effect is the Phantom Array, caused by an observer moving their eyes between two points in the visual field, which can cause the perception of side-by-side double images. The latter is the most applicable to aviation related lighting as pilots move their eyes back and forth on the airfield during flight maneuvers (e.g., landing, takeoff). These visual effects may be heightened in LED lighting when compared to incandescent lighting.

In particular, dimming an LED light with PWM may have an effect on the likelihood of experiencing a stroboscopic effect, particularly when the modulation frequency is less than 80 Hertz (Hz). An infrastructure design that allows for the dimming of LED lighting as well as reduces PWM can help reduce the stroboscopic effect. The Flicker Index describes the modulation of a light source; Bullough (2012) presented a model to describe the acceptable level of flicker index for various applications. Based on the model, even when stroboscopic effects are detectable, the effect may still be at an acceptable level.

A circuit design that was able to reduce flicker and increase electrical efficiency was described. The optimum metrics for the circuit included a flicker reduction of 33%, a power factor of equal or greater than 0.7, and an overall power efficiency of equal or greater than 85%. The circuit completes the task by using two LED arrays in reverse parallel, controlling the phase shift by overlapping the arrays. This reduces the stroboscopic effect by filling any potential light void.

Canter, G., Freyssinier, J. P., DiPilato, M., & Gallagher, D. (2017). *Development of Infrared Specifications for Night Vision Goggle-Compatible Light-Emitting Diode L-810 and L-864 Obstruction Light Fixtures* (Report No. DOT/FAA/TC-17/69). U. S. Department of Transportation, Federal Aviation Administration. https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/155/Development-of-Infrared-Specifications-for-Night-Vision-Goggle-Compatible-Light-Emitting-Diode-L-810-and-L-864-Obstruction-Light-Fixture

Red LED light emissions are outside of the wavelength spectrum that is used by NVGs. This is concerning as obstruction lights using red LEDs may not be visible while using these advanced vision systems. This report outlined the guidelines for using infrared performance metrics in obstruction lighting. Structures at or above 200 feet Above Ground Level (AGL) must meet standards for obstacle avoidance lighting, set by the FAA.

Obstacle avoidance lights must have a steady red light and a flashing red light at the rate of 30 flashes per minute and provide adequate time for a pilot flying at 165 knots (kt) to be able to detect the obstacle at least 2,000 feet horizontally during all weather conditions. Filters used in NVGs that are compatible with cockpit lighting also filter out light produced by red LEDs by restricting light below 665 nm, allowing for green, blue, and yellow lights to be used on the flight deck. Red LED lights can be seen while using NVGs if the light produced is within the filter limits. Other countries have included a mandate for an infrared light emitter to accompany any red LED obstacle lighting with the same constant/flash specification.

Through laboratory and field testing, it was determined that L-810 infrared fixtures provide enough signature for pilots to detect the obstruction lighting for up to 3.1 statute miles and enough time for a pilot to avoid coming within 2,000 feet horizontally from the obstruction. Furthermore, field testing confirmed infrared emission of at least 4 milliwatts (mW)/ steradian (sr) at a wavelength of 800 – 900 nm provided adequate visibility at a distance of 3.1 statute miles.

Davis, R. G., & Wilkerson, A. M. (2015). *Philadelphia International Airport Apron Lighting: LED System Performance in a Trial Installation* (No. PNNL-24816). Pacific Northwest National Laboratory, Richland, WA (United States). https://www.energy.gov/sites/default/files/2015/11/f27/2015_gateway_philadelphia-airport.pdf

Although the use of LED lighting for exterior applications has increased, their utility for certain exterior lighting applications needs further evaluation. An example is area lighting when the light is mounted at a height of 65 feet or greater. This high-mast lighting application requires a light output that exceeds that which is available by most LED lighting sources used for exterior applications (i.e., 750 or 1000 high-intensity discharge systems).

This report details a Department of Energy-funded field study in which LED lights were installed for apron lighting at Philadelphia International Airport. It was noted that apron lighting represents 25% of the total energy usage at the airport—which is the largest single energy user at many airports. Apron lighting provides light for operations at the gate such as pre-flight checks, fueling, baggage handling, and minor maintenance. If LED lights could offer significant savings in energy and maintenance and a potential safety benefit.

For the field evaluation, LED luminaires were mounted on poles to illuminate an area of the airport apron. Luminance data was collected from an existing high-intensity discharge lighting system as well as for the newly installed trial LED system, in apron areas where baggage handlers and other ground crew operate. The LED system exceeded the average luminances provided by the high-intensity discharge system. This was particularly true for luminance measurements taken between a distance of 15 feet and 180 feet from the pole. Beyond that distance, the LED system lost its advantage and slightly trailed the high-intensity discharge system. Some of the LEDs in the luminaires had malfunctioned and could not be replaced within the timeline of the study. The LED system could improve with a fully functioning system, except for those measurements taken from the longest distances from the pole.

Kahne, S., & Zeidlik, T. (2005). *Analysis and Evaluation of LED Threshold Lamp* [Unpublished manuscript]. U. S. Department of Transportation, Federal Aviation Administration.

This report details a one-year field test of LED lights installed at two US airports. An LED threshold lamp system was installed at airports representing two extreme climates—Grand Forks International Airport, Grand Forks, ND (GFK; extreme cold), and Phoenix Sky Harbor International Airport, Phoenix, AZ (PHX; extreme heat). The traditional incandescent lamps used for the green threshold lighting component of an ALS were replaced with green LED lamps on runway 7R at PHX and runway 35L at GFK. All other lamps used for ALS and the runway were incandescent light sources. Light intensity was measured every two months, and surveys were administered to pilots landing on those runways.

The metrics associated with lamp intensities did not change significantly over the test period. The LED lamps were found to be highly reliable, with the only failures associated with circuit failures in the alternating current (AC)/direct current (DC) converters rather than failures of the LED lamps themselves. To illustrate this point, during the one-year test, none of the one-watt LEDs failed among the 936 that were used.

Approximately 59% of surveyed pilots reported detecting a difference in the ALS, with the majority indicating that brightness and color were clear and that the ALS was easy to see. Most pilots who detected a change in the ALS noted that the threshold lights appeared brighter.

However, there were no significant HF issues identified during the one-year evaluation of the LED green threshold lighting system. The majority of pilots reported that they did not experience confusion related to the ALS.

Radetsky, L. C., Skinner, N. P., Narendran, N., & Bullough, J. D. (2014). *Can the Intensity of LED-Based Runway Guard Lights Be Reduced?* (Report No. S10109) [Paper presentation]. 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, N. J. https://www.airporttech.tc.faa.gov/Collaboration/Past-Conferences-Events/Airport-Technology-Transfer-Conference-2014/PgrID/4468/PageID/1

The use of LED lights for Elevated Runway Guard Lights (ERGL) may present certain challenges for brightness levels. Brightness level, optimum flash frequency, and duty cycles for incandescent and LED sources were evaluated for runway guard lights. The study was conducted in three phases. Phase 1 determined the minimum level of brightness for incandescent runway guard lights. Reaction times were shorter for high-intensity lights, with misses occurring at the current recommended levels; the longest reaction times were associated with lower-intensity lights. Phase 2 determined the most effective combination of flash and duty cycles. The most effective response times were seen in the study using a flash rate range of 1.25 to 2.50 Hz with 30 – 70% on time. Phase 3 determined minimum brightness for LED-based ERGLs, and consisted of a field study to determine the best LED brightness for runway and taxiway applications. Results indicated that LED-based lights at about one-third the luminance intensity prescribed for incandescent lights produce the best conspicuity. LED-based guide lights are comparable to or better than incandescent lights at reduced ambient lighting levels, if at the appropriate frequencies.

Snyder, C., Scarpone, C., Samiljan, R., Mackey, S. (2021). *LED Airport Lighting Behavior in Real-World Conditions* (Report No. DOT-VNTSC-FAA-21-04). U.S. Department of Transportation, John A Volpe National Transportation Systems Center. https://rosap.ntl.bts.gov/view/dot/55248

This nine-month field study at the Volpe Aviation Weather Research Facility evaluated LED lighting properties under a variety of visibility and weather conditions. The types of lamps evaluated were from ALSs (i.e., Medium-Intensity ALS), and runway edge lights (i.e., High Intensity Runway Lights). In all conditions, LED lighting was set to maximum intensity, and video data were used to derive contrast ratio values for both LEDs and incandescent lighting. Across all reduced visibility and weather conditions (e.g., fog, rain, snow) LEDs were brighter, and thus easier to see, than their incandescent counterparts. When comparing LED lamps in fog to LED lamps in rain, higher contrast ratio values were observed during rain. However, this might be due to features of the visibility measuring equipment itself which tends to underestimate visibility in rain. Contrast ratios of LEDs and incandescent lamps were lower in snow compared to rain or fog which may be due to the reduced contrast between a bright lamp and white snow background. Additional data would be needed to further explore this relationship. The results of this study suggest that LEDs are brighter than their incandescent counterparts in reduced visibility conditions and that LEDs may be easier to visually detect at distances where incandescent lighting is just barely distinguishable from the background.

Stevens, H. (2010). *Pilot Perception of Light Emitting Diodes Versus Incandescent Elevated Runway Guard Lights* [Master's thesis]. Embry-Riddle Aeronautical University. https://commons.erau.edu/cgi/viewcontent.cgi?article=1137&context=edt

In this study, pilot's perceptions of LED lighting were compared to incandescent lighting as used for ERGLs. LED and incandescent lights were used for ERGLs and installed at an airport in Daytona Beach, Florida, and pilots were asked to complete a survey while an instructor pilot taxied past the ERGL. Perceived brightness, noticeability, preference, and levels of distraction were measured. Tests were performed under daylight, dusk, and nighttime conditions. Pilots were classified as novice or expert depending on whether or not they had 200 flight hours or more of experience. Ultimately, the results suggested that LEDs were more noticeable, brighter, and more distracting. Pilots also indicated a preference for the LED ERGLs over the incandescent ERGLs. Further research is recommended to mitigate the level of distraction associated with LED ERGLs, perhaps through modification of flash rate, brightness, or lamp angle.

Yakopcic, C., Puttmann, J., Kunz, B. R., Ang, C., McPherson, A., Santez, D., Donovan, M., Skarzynski, J., Trick, J., Mead, A. M., Milburn, N., & Khaouly, N. E. (2013). *Experimental Effective Intensity of Steady and Flashing Light-Emitting Diodes for Aircraft Anti-Collision Lighting* (Report No. DOT/FAA/AM-13/15). U. S. Department of Transportation, Federal Aviation Administration. https://www.faa.gov/data_research/research/med_humanfacs/oamtechreports/2010s/media/201315.pdf

LEDs emit a spectral output that is different from traditional incandescent bulbs, which may affect viewer detection. Previous research has shown that with incandescent lights, flashing patterns result in a perceived brightness that is different from actual brightness. This perceived brightness (effective intensity) has been mathematically modeled in several different ways. Human participants who tested within 20/30 visual acuity observed lights in several different flash (pulse) patterns. Light patterns varied in pulse time length as well as brightness. A "visibility threshold" was calculated for each participant and at each pulse time length; these were combined to calculate a mean for each pulse time length across participants. Calculations were compared against predictions from the Blondel-Rey, Allard, and Modified Allard models. Results suggest that while the Modified Allard model produced the best predictions, the researchers recommend using the Blondel-Rey model to produce acceptable and conservative results.

Appendix C

LED Airfield Hardware Annotations

Bullough, J.D. (2012). *Issues with Use of Airfield LED Light Fixtures* (ACRP Synthesis No. 35). U. S. Department of Transportation, Federal Aviation Administration, Transportation Research Board. https://ntrl.ntis.gov/NTRL/dashboard/searchResults/titleDetail/PB2012108784.xhtml

Representatives of both domestic and international airports have started to consider the use of LEDs in airfield lighting applications because they are more durable and efficient, offer better color saturation, and reduce time for on/off (removing the need for moving parts to flash). Taxiway and runway lights are used to mark critical areas of the runway for pilot identification, including touchdown area, centerline guidance, and other navigational markings for takeoffs and landings. In particular, taxiway lighting provides route guidance both to and from the terminal.

Bullough reviewed literature and survey data from airport personnel who had experience with LED lighting on runways and taxiways. Representatives from 22 US airports and 2 European airports completed the questionnaire. Airport types in the survey pool included large to small hubs, noncommercial and non-primary hubs, general aviation airports, and military airports.

One concern is that LEDs produce little to no infrared energy, thus producing little to no heat that can prevent snow and ice build-up on the lens. Airports operating in extremely cold temperatures reported using heating elements in conjunction with LED lighting systems to counter this issue. Many of the respondents had replaced incandescent lights with LED fixtures while retaining the original electrical infrastructure. Energy savings and efficiency would increase if the electrical infrastructure were replaced to better meet the demands of LEDs.

Another concern was the higher up-front costs of LEDs compared to incandescent lights. The majority of survey respondents reported maintenance cost reduction and energy conservation as the primary reason for installing LED lighting. LEDs have a significantly longer life cycle than incandescent light sources and may last for 100,000 hours (compared to 2,000 hours with an incandescent lamp). LEDs use about a quarter to a third of the energy used by incandescent light sources. The majority of respondents indicated installation of LED lights was easy and required no specialized equipment, suggesting that installing an LED system is not an unreasonable task.

Installing LED fixtures on existing infrastructure reduced energy consumption by 50 – 70%. Installing smaller transformers with LED fixtures reduced energy consumption by 60 – 80%. Replacing infrastructure with LED fixtures reduced energy consumption by 87 – 98%. Some identified concerns included: (a) LED fixtures failing to last for the duration of the expected life cycle; (b) LEDs producing reduced light output; and (c) LEDs failing to work with existing control or regulator systems.

The majority of respondents reported that their LED replacement projects were funded by the Airport Improvement Programs; other funding came from facility charges and Federal stimulus funds. Half of the respondents reported that their cost savings were as planned, but were unsure if the initial investment had been returned. The majority of respondents indicated that their future plans are to install more LED runway and taxiway lights.

Chao, C., Chen, H., & Tsai, Y. (2021). Cost assessment model of airport runway lighting systems with consideration on carbon emissions. *Journal of Aeronautics, Astronautics and Aviation, 53*(1), 67-82. http://dx.doi.org/10.6125%2fJoAAA.202103_53(1).06

A model was presented to help evaluate the cost of airport runway lighting systems. This model, which incorporated carbon emissions, helped to compare the number of lights including lower-consumption sources, such as ceramic metal halide lights, fluorescent lights, and LED lights. Additionally, the model accounted for luminance decay, in which bulbs decrease in output over time until they must be replaced. Light and fixture costs were also included. Because airfield lights have different uses, light use was calculated for the time of day (e.g., lights only needed at night) and for time of year. Maintenance costs were calculated to include not only the replacement of burned-out bulbs but also the cleaning of dirty fixtures to help maintain luminance and extend service life. An example cost analysis for Kaohsiung International Airport was provided regarding electricity; installation, maintenance, and carbon costs were discussed in detail. It was noted that the difference in costs between traditional (halogen) and LED systems were dependent on electricity costs; LED lights had higher setup and maintenance costs than halogen lights but used less electricity. LEDs provided a benefit in lower electricity use (and thus fewer carbon emissions).

Cyrus, H. M. (2005). *Light Emitting Diode Taxiway Edge Lights Emissions Evaluation* (Report No. DOT/FAA/AR-TN05/10). U. S. Department of Transportation, Federal Aviation Administration. https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/93/Light-Emitting-Diode-Taxiway-Edge-Lights-Emissions-Evaluation

Certain LED taxiway edge fixtures may produce electrical emissions that might interfere with other airfield equipment. Here, five different lights were tested using a testbed (i.e., not at an operational airfield). The electrical emissions characteristics of the five tested fixtures were provided in detail. It was noted that four of the five tested fixtures were generating harmonic and nonharmonic emissions that had the potential for interference with other airfield equipment. This may be of particular concern, given that hundreds of fixtures may be wired to a single circuit.

Recommendations for future assessments include testing for compatibility with other airfield equipment, testing transformers with each fixture type to examine power consumption, testing on a larger circuit as found on an airfield, identifying a way to electronically identify failed lamps, and determining the efficiency of new fixtures.

Cyrus, H. M., & Nadel, J. (2008). *Light Emitting Diode Taxiway Lighting Effects on Constant Current Regulator Stability* (Report No. DOT/FAA/AR-TN08/29). U. S. Department of Transportation, Federal Aviation Administration. https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/76/Light-Emitting-Diode-Taxiway-Lighting-Effects-on-Constant-Current-Regulator-Stability

Constant Current Regulators (CCRs) are used on airfields to provide a selected current and are used in airfields to provide electrical current to lighting fixtures. LEDs are known to present novel load characteristics, which may cause improper CCR function (e.g., turning off due to overvoltage or overcurrent that may be normal for LED lights but abnormal for incandescent lights). A testbed was developed and used to examine the behavior of five types of LED taxiway edge fixtures. Two of the tested fixture types were found to show significant loading at power-up.

Recommendations for future LED taxiway lighting fixtures are provided. First, the peak load of an LED fixture should not exceed 10% above nominal operating power. Second, LED fixtures should not suddenly drop load by more than 10%. These two recommendations will allow CCRs enough reserve capacity to support the higher load seen at startup and not trip off due to overcurrent conditions when the load drops. The following four factors should be considered: (a) designers of airport taxiway lighting circuits take into account peak and nominal loads into designs (b) CCR behavior should be considered when selecting LED fixtures and CCRs (c) manufacturers should be consulted during the design process, and (d) attention must be paid to circuits that include LEDs and other equipment with high initial peak loads.

Gallagher, D. W. (2005). *Evaluation of Light Emitting Diode Linear Source Devices* (Report No. DOT/FAA/AR-05/2). U. S. Department of Transportation, Federal Aviation Administration. https://www.airporttech.tc.faa.gov/Products/Airport-Safety-Papers-Publications/Airport-Safety-Detail/ArtMID/3682/ArticleID/94/Evaluation-of-Light-Emitting-Diode-Linear-Source-Devices

An interim report (Gallagher, 2001) preceded this final report and is omitted from the annotated bibliography. In this report, paint markings on airport surfaces were enhanced with LEDs. The results from this evaluation were promising. The LEDs were found to be visually effective and, when placed in close proximity (i.e., in a row), continued to provide effective markings in the event one LED were to burn out. However, off-the-shelf LED lighting strip equipment were not found to be robust in testing. Plastic material cracked, equipment were not watertight, or were otherwise damaged by standard airport operations (e.g., snow removal equipment damaged some lighting hardware during testing).

In addition, the plastic support material in the tested equipment did not aim the LEDs at a consistent angle, resulting in varying brightness across LEDs. LED equipment should be improved to handle the relatively harsh airport environment before they are adopted for use more widely. Additional outstanding questions were identified for follow-on research: (a) how will LED lighting interact with incandescent lighting; (b) how will LED intensity interact with human visual perception; and (c) how will narrow-spectral-band light from LEDs interact with pilots who have certain color vision deficiencies?

Gu, Y., Baker, A., & Narendran, N. (2007). Investigation of thermal management technique in blue LED airport taxiway fixtures. In *Seventh International Conference on Solid State Lighting* (Vol. 6669, pp. 164-168).. International Society for Optics and Photonics. https://www.lrc.rpi.edu/programs/solidstate/pdf/Gu-SPIE6669.pdf

Blue light fixtures used to mark taxiways must be visible in all weather conditions; that is, they must be free of ice and snow in winter. The move to LED lighting is problematic because LEDs do not generate enough heat to melt ice and snow in the same way as incandescent lamps. This report presents a novel method to draw heat away from the LED to the outside of the fixture. FAA requirements for a blue-glass cover and minimum heat emission could be met with the addition of a small heater, but it was noted that fixture design and FAA requirement changes could result in a fixture requiring no additional heater to generate a level of heat equivalent to that found on the outside of traditional incandescent fixtures.

Hayton, J. P. (2016). *Development of Mid-Infrared Light Emitting Diodes to Replace Incandescent Airfield Lighting* [Doctoral dissertation]. Lancaster University. https://eprints.lancs.ac.uk/id/eprint/86080/1/Master.pdf

In the move to LEDs on the airfield, there is a need to focus on replacing the infrared component emitted by incandescent lamps. Some advanced vision technologies, such as EVS and EFVS, require an infrared signal for proper operation. In particular, there is a need for an LED replacement that emits 2μm infrared light for use in ALSs. This thesis included a description of the development and testing of new technology for LEDs that would be needed in order to emit 2μm infrared light. The research was successful in developing an LED that emitted 2μm infrared light, but an LED device that can generate a sufficient output of infrared light useful to EFVS was found to be too large. Instead of a direct replacement for incandescent bulbs in an ALS enclosure, the newly developed LED technology requires approximately 20 to 40 devices working in combination. A recommendation was made to modify the design of existing ALS enclosures, as well as further modifications that can be made to the newly developed 2µm infrared LEDs.

Johnson, C., & Dermody, J. R. (2015, May 7). *LEDs in Aviation Lighting* [PowerPoint presentation]. IESALC. Meeting. http://www.iesalc.org/?wpfb_dl=493

Replacing incandescent with LED lighting in airfield applications has its pros and cons. This presentation focused on approach lighting, runway lighting, taxiway lighting, and obstruction lighting. Overall, the pros were that LEDs are more efficient and are considerably brighter to the naked eye. The cons are that they may be too bright for the naked eye at night. Additionally, certain vision systems, such as NVGs and EVSs, struggle to detect (or fail to detect altogether) the light emitted by LEDs. Based on pilot surveys (65% negatively reviewed LEDs) and these technical discoveries, further research is suggested to determine how these lighting systems should be used in airfield applications.

Kerr, J. R. (2008, April). Enhanced detection of LED runway/approach lights for EVS. In *Enhanced and Synthetic Vision 2008* (Vol. 6957, p. 695703). International Society for Optics and Photonics. https://doi.org/10.1117/12.764684

A technique for improving the acquisition of pulsed LEDs by EVS cameras was proposed. This technique was thought to be especially helpful when conducting low visibility landing or ground operations in the presence of fog. As an overview, the synchronization of pulsed LEDs with aircraft EVS cameras can be accomplished through GPS timing signals. As a benefit, the data decoding only requires inexpensive electronics. EVS with a 60 Hz refresh rate were programmed to coordinate GPS data with LEDs set on a specific cycle (30 Hz, exactly half the refresh rate) to combine into a synchronous information stream. This technique combines data to the user in real-time while constructing a consistent EVS image. This was done by introducing shortwave infrared (SWIR) diodes or mid-wave infrared (MWIR) diodes, because visible-wavelength LEDs do not emit light that could interfere with data transmission using SWIR or MWIR. The prototype EVS system successfully received data using this mechanism.

Kopp Glass. (2011, May 1). Airfield lighting heated lens. *Tech Briefs*. https://www.techbriefs.com/component/content/article/tb/supplements/lt/features/applications/14329

A novel heated lens can potentially overcome the frosting issues related to LED light fixtures in arctic or other cold winter weather conditions. Kopp Glass was reported to mitigate the buildup of ice that obscures the light output, while also saving more energy overall compared to previous incandescent bulbs. Thus, the article concluded that there is potential in combining the energy efficiency of LEDs with the implementation of Kopp Glass lenses to solve the ice-related light obscuring issue. Combining Kopp Glass lenses with LED lights was not expected to result in any issues affecting chromaticity.

Lean, D., Cyrus, H., & Brown, N. (2010). *Light-Emitting Diode Taxiway Edge Light Photometric Evaluation* (Report No. DOT/FAA/AR-TN09/56). U. S. Department of Transportation, Federal Aviation Administration. https://www.tc.faa.gov/its/worldpac/techrpt/artn0956.pdf

LEDs dim over time with use. The photometric performance (dimming), reliability, and durability of LEDs used as taxiway edge lights were examined. The photometric intensity of LEDs deteriorated to 77% intensity over a two-year test period, whereas incandescent lighting intensity deteriorated to 43% over the same period. Chromaticity is a concern for pilots with certain CVDs; the chromaticity of LEDs remained consistent during the test period. Only one LED required replacement, though it was due to the manufacturer's faulty equipment. LEDs were found to consume more power at lower intensity settings of the CCR, so recommendations were provided to improve CCR performance and improve power consumption. Recommendations for burn-in testing of equipment were also provided.

Marsh, L., Cole, R., Lanning, M., Sellers, N, & Nettey, I. R. (2008). *Light Emitting Diodes: An Efficient Choice for Airfield Lighting.* 2008 FAA Airport Design Competition for Universities. https://www.semanticscholar.org/paper/Light-Emitting-Diodes%3A-An-Efficient-Choice-for-Marsh-Cole/24aab6dc23d4759e49b273ec976768d109c92299

LEDs are expensive to install and have a narrow ambient temperature zone for operation. In cold climates, this means that LEDs used for airfield lighting must be accompanied by a heater. A comparison between LEDs, incandescent, and halogen lighting was provided, as well as a safety risk assessment and cost analysis. Light color requirements and deicing concerns were also are discussed. LEDs improved cost efficiency better than other lighting sources, and were capable of lasting through cold climates.

Montes, M. G., Vázquez, D., Fernandez-Balbuena, A. A., & Bernabeu, E. (2014). Beacon system based on light-emitting diode sources for runways lighting. *Optical Engineering, 53*(6), 066104. https://doi.org/10.1117/1.OE.53.6.066104

A prototype LED runway lighting fixture designed to meet International Civil Aviation Organization (ICAO) standards was presented. A prototyping process demonstrated that LED lighting fixtures could meet ICAO standards successfully. This included controlling for light output, modifying lighting housing, and meeting chromaticity standards. As a proof of concept, it was concluded that LED lighting is currently capable of meeting standards required by international regulators while saving on upkeep and energy.

Narendran, N., & Freyssinier, J. P. (2014). *How is the Operational Failure of LED Fixtures Identified?* [Paper presentation]. 2014 FAA Worldwide Airport Technology Transfer Conference, Galloway, N. J., August 4-8, 2014. https://www.airporttech.tc.faa.gov/Collaboration/Past-Conferences-Events/Airport-Technology-Transfer-Conference-2014/PgrID/4468/PageID/1

LED light sources are considered to have a much longer life cycle than incandescent light sources. However, the length of the increased life cycle and the characteristics of an LED approaching the end of its life cycle are not completely understood. Incandescent lights often experience a catastrophic failure at the end of a duty cycle whereas LED lights fade in luminance, falling outside the specification range. LED lights also depreciate and shift color. The industry standard to provide lifetime estimation is to time for the light to reduce output by 30%.

Photometric parameters might be the best way to define duty cycles for LEDs in airfield applications. When evaluating red and white runway lights and white touchdown zone lights for 10,000 continuous hours, three lights completely failed due to issues with the electrical circuits between 560 – 7,630 hours. Lights operating at about 55° Celsius (C) only reduced light output by approximately 6%. Operating temperatures between 59° – 80° C reached the threshold of 30% reduction in light output at about 9,000 operating hours. Among white lights, all samples experienced a chromatic shift toward yellow.

Perera, I. U., & Narendran, N. (2016). *Measuring the Temperature of High-Luminous Exitance Surfaces with Infrared Thermography in LED Applications.* In *Fifteenth International Conference on Solid State Lighting and LED-based Illumination Systems* (Vol. 9954, pp. 82-91). SPIE. http://doi.org/10.1117/12.2240650

Because LED components are sensitive to heat, temperature probes are used to examine the state of such lighting equipment in order to prevent degradation that can result in reduced safety. The accuracy of infrared cameras on measuring the heat generated by high-intensity LEDs was examined. Because camera measurements can be tuned to ignore light output, they are believed to be more accurate than thermocouple devices where light output causes temperature measurement error. Infrared cameras were able to predict surface temperature to within measurement accuracy (so long as the camera was aimed well). Infrared cameras provide an accurate alternative to thermocouple units for measuring temperatures of high-output LEDs such as those found on the airfield. They may provide an easier way to monitor LED systems remotely with lower cost.

Pérez-Ocón, F., Pozo, A. M., & Rabaza, O. (2017). New obstruction lighting system for aviation safety. *Engineering Structures, 132*, 531-539. https://doi.org/10.1016/j.engstruct.2016.11.054

A novel approach to reduce complexity while improving safety at aviation lighting installations was presented. In the proposed system, the beacon light source was placed at ground level, where it was presumed safer for maintenance crews to access. The light output from a ground-level light source was then channeled through fiber optic cables to where it was needed. This allowed the light to be channeled to locations that might be dangerous to maintenance crews, such as at the top of telecommunications towers (i.e., for use as obstruction lighting). In such an installation, maintenance to the light source, (i.e., replacing burnt-out bulbs) would occur on the safety of the ground. It is noted that this system could be beneficial to safety in any lighting structure used in aviation, especially as the presented LED-based hardware design exceeds ICAO lighting guidelines.

Petrick, J. T. (2002). High-brightness LEDs in aerospace applications. In *Solid State Lighting II* (Vol. 4776, pp. 34-50).SPIE. http://doi.org/10.1117/12.452576

While LEDs have been used in indoor indicator lighting for decades, the use of LEDs in outdoor conditions, such as airfields, is less common. LEDs must pass certain requirements in order to be used in aerospace applications, such as light intensity, a 24-hour LED burn-in period, chromaticity requirements for each color of light emitted, light output at various operating temperatures, compatibility with existing airport equipment, electrical characteristics requirements. Problems such as lack of detailed photometric specifications for many lights, poor longevity, proper thermal management (e.g., installation of heat sinks to carry away heat), and radio wave interference may prevent these requirements from being met. In certain circumstances, regulations might be reconsidered to allow the use of blue colors that LEDs can provide while helping to increase visibility in mesopic conditions (i.e., low-light environments such as nighttime street lighting).

Wang, S., Wang, K., Chen, F., Zhao, S., & Liu, S. (2010). A Novel LED lamp for the Middle Line of the Taxiway of the Airport. In *2010 11th International Conference on Electronic Packaging Technology & High Density Packaging* (pp. 1409-1411). IEEE. http://doi.org/10.1109/ICEPT.2010.5582828

The solid-state nature of LED lamps suggests higher reliability with higher luminous intensities. An optical structure was designed to produce a light distribution pattern that complies with relevant regulations (i.e., it must shine light where it is needed and required, but not elsewhere) and provides proper illumination for a taxiway middle line. Several issues were identified; 1) the materials in any new lamp must be able to withstand the pressure exerted by a passing aircraft, 2) the unit must be resistant to corrosion (i.e., weatherproof), and 3) the equipment must tolerate extreme temperature changes due to use outdoors.

Appendix D.

NASA ASRS Excerpts

The following excerpts from reports in the NASA ASRS database, between 2011 and 2019, were identified by searching for keywords related to LED lighting. These reports provide an indication of some concerns identified pilots in the US NAS.

> Use of LED lighting which is pure light, this produces high illumination levels which hurts our night vision. LED lights also cause a blooming effect during high moisture days. Lighting must be adjusted to suitable levels to not hurt our night vision. (DFW, Dallas Fort Worth International Airport, 2019)
>
> The double image is caused by the LED lighting and it appears to be like a prism or holographic effect in the windows or the aircraft. I wear glasses and so during taxi in I raised my glasses and had the same double image and my First Officer who does not wear glasses had the same double image. (MEM, Memphis International Airport, 2018)
>
> I am appalled by the LED lighting that has been going in around our airport systems in the last many years and have written other reports. This time there was potential for serious accident. Honestly, I believe no user has been involved in the choice of lighting. I have always felt the lighting is way too bright and not dimmable. ATC has gotten many requests to dim these non-dimmable lights. Crews now just suck it up as we do. (LAS, McCarran International Airport, 2018)
>
> 34R/16L has new LED centerline lights. They are so bright and intense on their lowest setting (confirmed by tower) that it makes final approach to landing difficult at night… The main problem is that the runway edge lights have not been replaced with the newer style LEDs... so you can barely even make out the runway edge lights, whereas the centerline nearly blinds you! (RNO, Reno-Tahoe International Airport, 2016)
>
> The runway lights must have been turned all the way up on high because of the weather conditions, and 35R was indeed the runway with LEDs, edge lights, centerline, and touchdown zone. It was so bright that I literally could not see the pavement when landing. (OKC, Will Rogers World Airport, 2014)
>
> Green LED taxi lights are far too bright at DEN, in this specific case, Taxiway CN by 7W nearing Mike Taxiway. The lights are so bright it floods the cockpit and blinds the Crew making it impossible to see beyond the lights right in front of you. This same thing happens on the runway centerline LEDs at DEN and other cities, far too bright. (DEN, Denver International Airport, 2014)
>
> During a nighttime visual approach into ATL Runway 26R I noticed the pavement lights on the runway flashing on and off. I also noted that the runway lights on the parallel

Runway 26L were also flashing on and off. I had another experienced pilot with me who saw the same thing. We discussed what was happening and thought it may be the propeller strobe effect and runway LED lighting. (ATL, Hartsfield–Jackson Atlanta International Airport, 2014)

If there were an animal, FOD, or even a human on the taxiway, we would be quite challenged to see it while blinded by these lights. Some airports have extremely bright approach lights and centerline runway lights as well that also blind us. I have asked ATC if they could lower them and I always get told that they are as low as they go in a frustrated and empathetic tone indicating that they are often requested to lower them. (Unspecified Airport, 2014)

When I landed, the lights throughout the airfield were on low and they were exceptionally bright. The excessive brightness, particularly in the approach and flare, can lead to a lack of depth perception and could lead to very poor landings and touchdowns. The lights are so bright it leads to a loss of night vision not unlike a light being flashed directly in your eyes. (ABQ, Albuquerque International Sunport, 2011)