Airport Parking Garage Lighting Solutions

DETAILS

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AIRPORT COOPERATIVE RESEARCH PROGRAM

ACRP REPORT 124

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AIRPORT COOPERATIVE RESEARCH PROGRAM

Airports are vital national resources. They serve a key role in transportation of people and goods and in regional, national, and international commerce. They are where the nation's aviation system connects with other modes of transportation and where federal responsibility for managing and regulating air traffic operations intersects with the role of state and local governments that own and operate most airports. Research is necessary to solve common operating problems, to adapt appropriate new technologies from other industries, and to introduce innovations into the airport industry. The Airport Cooperative Research Program (ACRP) serves as one of the principal means by which the airport industry can develop innovative near-term solutions to meet demands placed on it.

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Dr. Ronald B. Gibbons, Director of the CIBSS, is the Project Director and Principal Investigator. The other authors of this report are Paul Lutkevich, Jeffrey Berg, and Jonathan Weaver from Parsons Brinckerhoff and Joakim Karlsson and Doug Slocum from MCR Federal, LLC, as well as Matthew E. Palmer, Caroline Connell, and Arash Jahangiri, also from the Virginia Tech Transportation Institute.

FOREWORD

By Joseph D. Navarrete
Staff Officer
Transportation Research Board

ACRP Report 124: Airport Parking Garage Lighting Solutions provides guidance to help airport industry practitioners select the most appropriate lighting technologies for their unique parking garage conditions. Airports provide singular challenges to the design and operation of parking garages in general and to their lighting in particular. Users are frequently unfamiliar with the garage and under time constraints; atypical activities often occur (e.g., rental car operations); activity often occurs at night; and airports are high-security areas. The guidebook will be of interest to a wide range of airport practitioners, including landside planners, utilities managers, lighting specialists, operations and maintenance personnel, and customer service staff.

Recent advancements in lighting technologies provide new airport garage lighting options. Although these advancements have resulted in more choices, many airports may not have the information or expertise needed to select the most appropriate technologies to meet their unique operations. In addition, performance data for these new technologies are limited and obtained primarily from manufacturers. Research was needed to develop guidance to help airports objectively evaluate and select appropriate lighting technologies to meet their parking garage needs.

The research, led by the Virginia Tech Transportation Institute, began with a review of literature and current codes and practices recommended by industry associations. An assessment of current lighting technologies was then undertaken to identify their operational strengths and weaknesses. Next, to gain an understanding of the unique considerations that airport parking garages present, a data collection effort was undertaken. This effort consisted of user surveys and the collection of photometric data at eight airports representing a variety of lighting types, sizes, activity levels, and geographic conditions. Finally, the research team developed a process to consider the lifecycle cost of various approaches to airport garage lighting. The results of these efforts were used to develop suggested guidance for airports that considers an airport's operations, site conditions, and cost.

The guidebook's introduction focuses on the unique needs of airport parking garage lighting. Next, the guidebook provides an overview of the current state of the art in lighting technologies, including high pressure sodium, ceramic metal halide, fluorescent, induction fluorescent lamps, light-emitting diodes, organic light-emitting diodes, and light emitting plasma/plasma lamps. The guidebook then evaluates these technologies relative to a set of lighting goals. Based on these goals, it offers recommendations for illuminance level, emergency lighting, luminance (reflected light), and uniformity based on the location and functional elements of the garage, including drive aisles, ramps, pedestrian walks, drop-off/pickup areas, elevator lobbies, vehicular entrances/exits, and concession areas. The guidebook also provides building design considerations and addresses site planning, architecture, and light operation options. It concludes with guidance on weighing the benefits and costs of airport garage lighting options and provides examples for how the reader can identify and incorporate various considerations. A list of references and glossary are also included in the guidebook.

CONTENTS

CHAPTER 1

Introduction

Airports present a unique combination of issues for parking garage lighting. Security, wayfinding, retail issues, and usability are all considerations in airport garage lighting design. Currently, there is increased pressure to reduce costs and environmental impacts; these issues now have a greater weight than they used to. To allow an airport manager or a designer to balance these issues, ACRP Project 09-03 developed a guidebook for airport parking garage lighting, augmenting other standards such as RP-20 from the Illuminating Engineering Society (IES); the primary focus here is to identify the benefits of different lighting technologies, compare these factors in an airport parking garage application, and develop benefit-cost guidance for different lighting installations.

Parking garages and parking lots are unique areas of the transportation infrastructure. Because the purpose of a parking lot is to allow drivers to transition into pedestrians and pedestrians back into drivers, no element in the transportation infrastructure has a greater potential for pedestrian-vehicle conflicts. As a result, special lighting requirements must be considered for safety. For pedestrian comfort and usability, a design must consider, calculate, and incorporate not only the horizontal illuminance—the amount of light falling on a horizontal surface—but also the vertical illuminance. Horizontal illuminance provides the visibility of the roadway, and vertical illuminance provides the lighting for pedestrian recognition, vehicle detection, and general visual comfort.

Parking garages in particular pose a special challenge for lighting because, unlike parking lots, they are interior spaces where lighting is required 24 hours a day. Because parking garages must accommodate both vehicular and pedestrian traffic, the lighting must be adequate for all users to safely traverse the space at all times. Aboveground parking garages, however, allow daylight through the sides of the garage between levels, so there is an opportunity to take advantage of natural lighting and save energy. Leveraging natural lighting requires the garage-lighting system to be well designed and constructed, and to incorporate an appropriate control system.

Airport garages require additional design considerations beyond those of other garage types. Airport garage users conduct activities atypical in other garage types, such as renting vehicles. The users might be unfamiliar with the garage layout, because as locals they do not travel often, or because they are visitors to the area. They might be unfamiliar with the vehicle they are driving. They also might be anxious about beginning or ending a trip. Airport garage lighting can help unfamiliar and possibly anxious airport patrons better navigate the airport by improving illumination in rental areas, walkways, overhead signs, pay stations, elevators, and other important areas. Using lighting to aid wayfinding increases patron comfort. Additionally, a well-designed lighting system will increase the chances that pedestrians and vehicles will travel in predictable ways, increasing overall safety.

Finally, airport garages face challenges because they are located near airports—high-security facilities. Lighting in general, and vertical illuminance in particular, aid in facial recognition and activity detection, so higher levels of vertical illuminance are required in spaces where security is a concern.

CHAPTER 2

State of the Art in Lighting Technologies

Electric lighting technology is over a century old, and the industry is constantly changing. From incandescent to fluorescent, from high intensity discharge to light-emitting diodes, the range of lamp options is vast. Lamp technologies have been evaluated and compared before now, but not with respect to airport garage lighting.

Airport garages require lighting that has high levels of vertical illuminance, low glare, energy efficiency, and controllability. Here, various lamp technologies are described and evaluated based on how well they can be applied to airport garage lighting.

2.1 High Pressure Sodium (HPS)

HPS lamps have been used for indoor and outdoor parking lighting, as well as most other exterior lighting applications, for the last 20 years. The lamp is a high intensity discharge (HID) lamp that excites sodium, contained in an arc tube, to produce light. Current regulation to the lamp is produced with an induction ballast. HPS lamps are available in a very wide range of wattages and lumen outputs and are considered one of the highest-efficiency HID sources. An example of an HPS lamp is shown in Figure 1.

Lamp envelopes are available either as clear or coated, with clear being the most common. HPS lamp light is yellow-gold, and it has a low color rendering index (CRI), so people tend to find it difficult to distinguish colors in areas lit with HPS lamps.

The performance metrics of an HPS lamp typically used for parking structures and lots, an Osram-Sylvania Lumalux Ecologic lamp, are shown in Table 1. The data are from a range of Osram-Sylvania lamps, LU50/ECO to LU400/ECO.

Factors to be considered with HPS lighting include:

Temperature: There are no ambient temperature concerns with HPS lamps.

Lumen maintenance: The lumen depreciation of HPS lamps is good, with the output declining to approximately 75% to 84% of initial lumens by the rated end of life, as shown in Figure 2.

Fixture efficiencies: Because HPS arc tubes are relatively small, allowing for better reflector designs, this light source it is considered fairly efficient at directing the lamp lumens to the surfaces requiring lighting.

Controllability: HPS sources have a warm-up and a restrike time. The restrike time is a consequence of the lamp, once turned off, needing to be cool before the arc can be re-established. A typical lamp takes three to four minutes to stabilize from a cold start and about one minute to restrike after momentary power interruptions. This makes HPS unsuitable for switching requiring instant startup. There are, however, dimming systems that can be used with HPS lamps, offering some suitability for adaptive control systems.

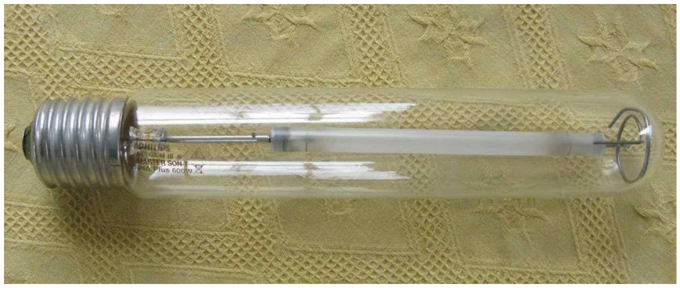

Figure 1. Example high pressure sodium lamp. Source: http://en.wikipedia.org/wiki/Sodium-vapor_lamp#mediaviewer/File:SON-T_Master_600W.jpg

Table 1. Lamp characteristics: high pressure sodium.

Lamp lumen/watt	80 to 125
System Efficacy lumen/watt	61 to 107
Rated Life (based on 35% mortality)	30,000 hrs
Rated Life (based on 70% lumen output)	30,000 hrs
Correlated Color Temperature (CCT)	1900K to 2100K
Color Rendering Index (CRI)	22

Source: Data from Osram-Sylvania technical specifications, compiled by Parsons Brinckerhoff

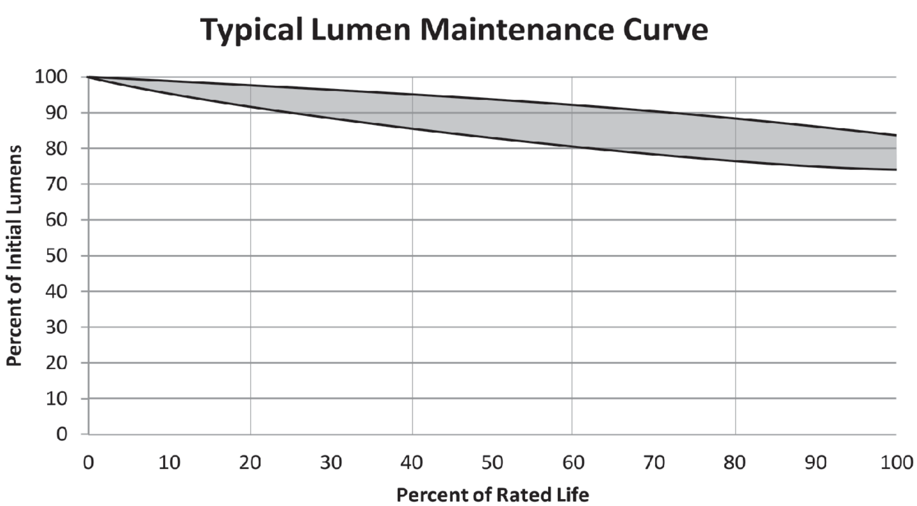

Figure 2. Lumen maintenance of typical high pressure sodium lamp. Source: Compiled by Parsons Brinckerhoff.

Figure 3. Example ceramic metal halide lamp. Source: http://en.wikipedia.org/wiki/Metalhalide_lamp#mediaviewer/File:150_Watt_Metal_Halide.jpg

2.2 Ceramic Metal Halide (MH)

MH sources have been one of the key alternative HID options to HPS lamps when white light is desired. In the past, MH lamps were considered fairly efficient, but they had a much shorter rated life than HPS lamps. MH lamps also had other drawbacks, including color shifts during their operating life and some failure issues. However, developments in ceramic metal halide technology have considerably increased the lamp's efficiency and life. A typical MH lamp is shown in Figure 3.

The performance metrics of typical MH lamps for parking structures and lots are shown in Table 2. Data are from a range of Philips MasterColour Elite lamps.

Factors to be considered with ceramic MH lighting include:

Temperature: There are no ambient temperature concerns with metal halide lamps.

Lumen maintenance: The lumen depreciation of ceramic MH lamps is quite low, with the output declining to approximately 90% of rated lumens by 16,000 hours, as shown in Figure 4.

Fixture efficiencies: Because an MH lamp is relatively small, allowing better reflector design, it is considered fairly efficient in directing the lamp lumens to the surfaces requiring lighting.

Controllability: MH sources have a warm-up and a restrike time. A typical lamp takes 1.5 to 2 minutes to stabilize from a cold start and about 10 minutes to restrike after momentary power interruptions. This makes MH unsuitable for switching required by instant startup operation. There are, however, dimming systems that can be used with MH lamps, offering some suitability for adaptive control systems.

Table 2. Lamp characteristics: ceramic metal halide.

Lamp lumen/watt	105 to 120
System Efficacy lumen/watt	100 to 111
Rated Life (based on 50% mortality)	24,000 hrs
Rated Life (based on 70% lumen output)	24,000 hrs
Correlated Color Temperature (CCT)	3000K to 4200K
Color Rendering Index (CRI)	90

Source: Data from Philips MasterColour Elite lamps technical specifications, compiled by Parsons Brinckerhoff

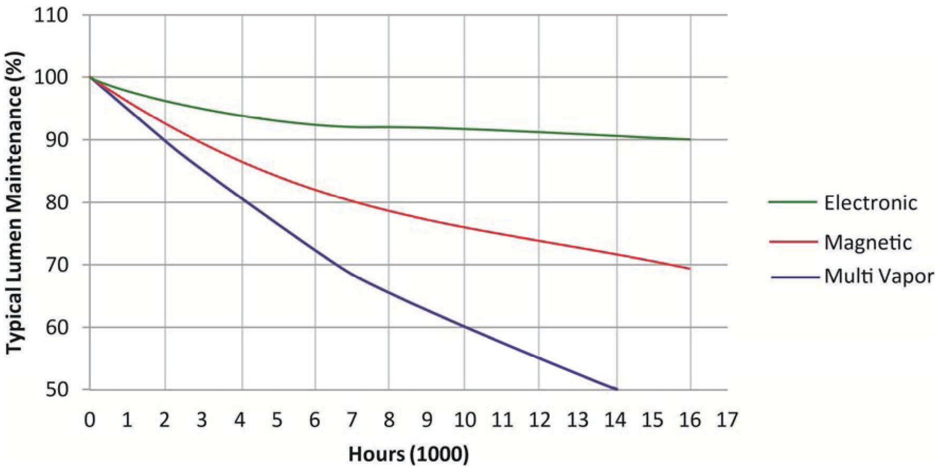

Figure 4. Lumen maintenance of typical metal halide lamp. Source: Compiled by Parsons Brinckerhoff.

2.3 Fluorescent Lamps (FL)

Linear fluorescent lamps have often been used for parking garage lighting. The sources have long lives, are efficient, and sometimes offer instant on/off and some degree of dimming in low brightness, white light sources. Example FL lamps are shown in Figure 5.

The performance metrics of a typical FL lamp used in parking lots, an Osram-Sylvania T8 reduced mercury 4-ft lamp, are shown in Table 3. The data are from a single Osram FO32/800/XPS/ECO3 lamp.

Factors to be considered with fluorescent lamps include:

Temperature: Depending on the ballast and lamp type, there are limitations to the temperatures at which an FL lamp will effectively start. The example shown in Figure 6 uses programmed rapid start ballast, and its minimum starting temperature is −18°C (0°F). For some energy-saving

Figure 5. Example fluorescent lamps. Source: http://en.wikipedia.org/wiki/Fluorescent_lamp#mediaviewer/File:Leuchtstofflampen-chtaube050409.jpg

Table 3. Lamp characteristics: fluorescent.

Lamp lumen/watt	97
System Efficacy lumen/watt	85 to 98
Rated Life (based on 50% mortality)	40,000 hrs
Rated Life (based on 70% lumen output)	40,000 hrs
Correlated Color Temperature (CCT)	3000K to 6500K
Color Rendering Index (CRI)	81 to 85

Source: Data from Osram-Sylvania technical specifications, compiled by Parsons Brinckerhoff

lamps, the starting temperature can be as high as 16°C (60°F). In addition, FL lamps have different outputs depending on temperature. Fluorescent lamps in the T8 (one inch diameter) category are usually rated for a 25°C (77°F) ambient temperature. Temperatures above and below this rated temperature produce fewer lumens than the lamp rating. Temperature around the lamp inside the fixture (luminaire) is dependent upon fixture design, but in garage installations, output will be less in periods of severe cold or heat.

Lumen maintenance: The lumen depreciation of many linear fluorescent lamps is quite favorable, as shown in Figure 7. The Octron XPS lamp will maintain approximately 94% of its initial lumen output throughout its rated life.

Fixture efficiencies: Because linear FL sources are large, FL luminaires are generally not considered highly efficient in directing the lamp lumens to the surfaces requiring lighting. However, the large size considerably reduces glare.

Controllability: Linear FL sources are instant-on, requiring neither strike nor extended warm-up time. They can also be dimmed using dimming ballasts. The programmed start ballasts used in many of these fixtures are often rated for more than 100,000 switching cycles, making FL lamp technology amenable to frequent power cycling required by daytime and occupancy controls.

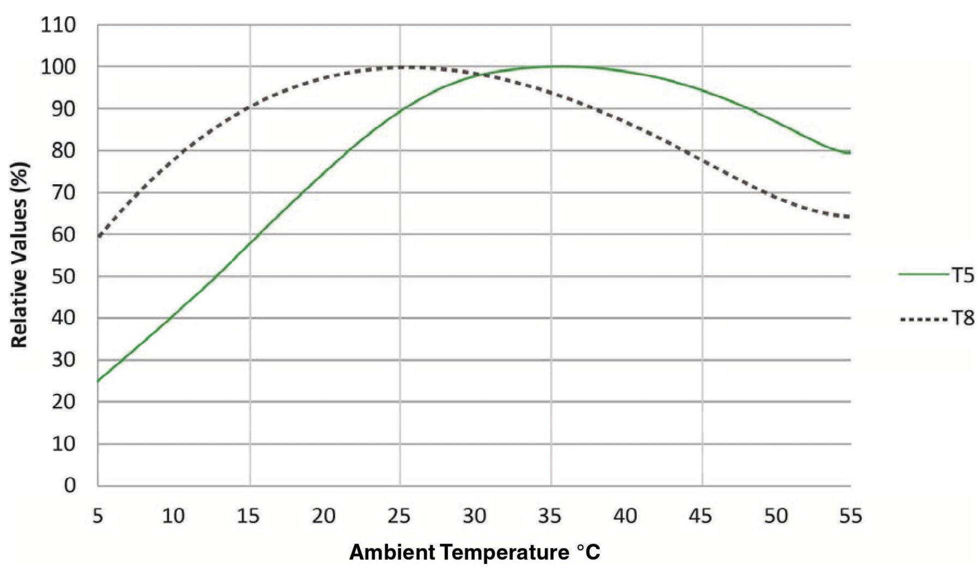

Figure 6. Ambient temperature-to-output relationship for fluorescent lamps (range is from 41°F to 131°F). Source: Compiled by Parsons Brinckerhoff.

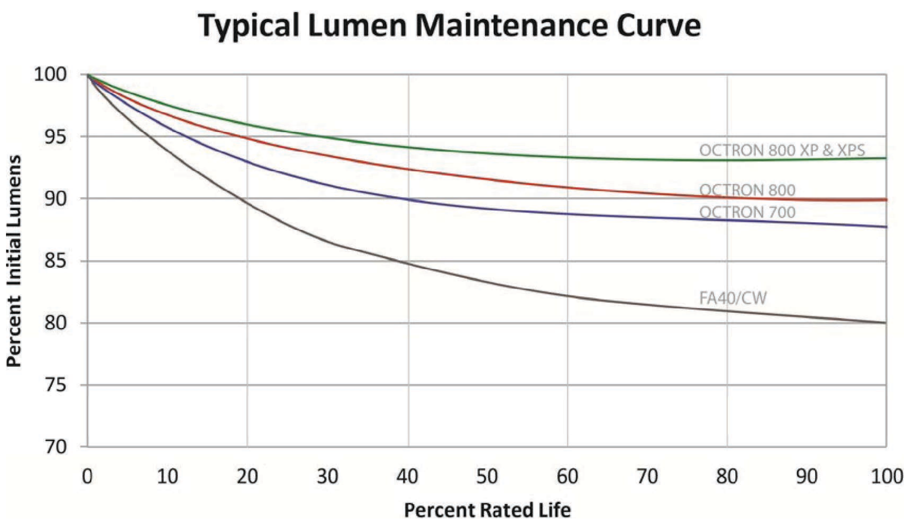

Figure 7. Lumen maintenance of typical fluorescent lamps. Source: Compiled by Parsons Brinckerhoff.

Despite having good CRI, FL lamps had the lowest rating for color recognition in an airport garage patron survey. As with the results for HPS lamps, few survey respondents means that these surprising results are not robust.

2.4 Induction Fluorescent Lamps (IFL)

IFL lamps are a fluorescent-based technology using a magnetic-induction coil, as opposed to electrodes, to excite the lamp phosphors and generate light. This greatly extends the expected life of the lamp. Example light sources are shown in Figure 8.

Various wattages and envelope types are available from different manufacturers. All of the wattages can be used in a parking garage installation.

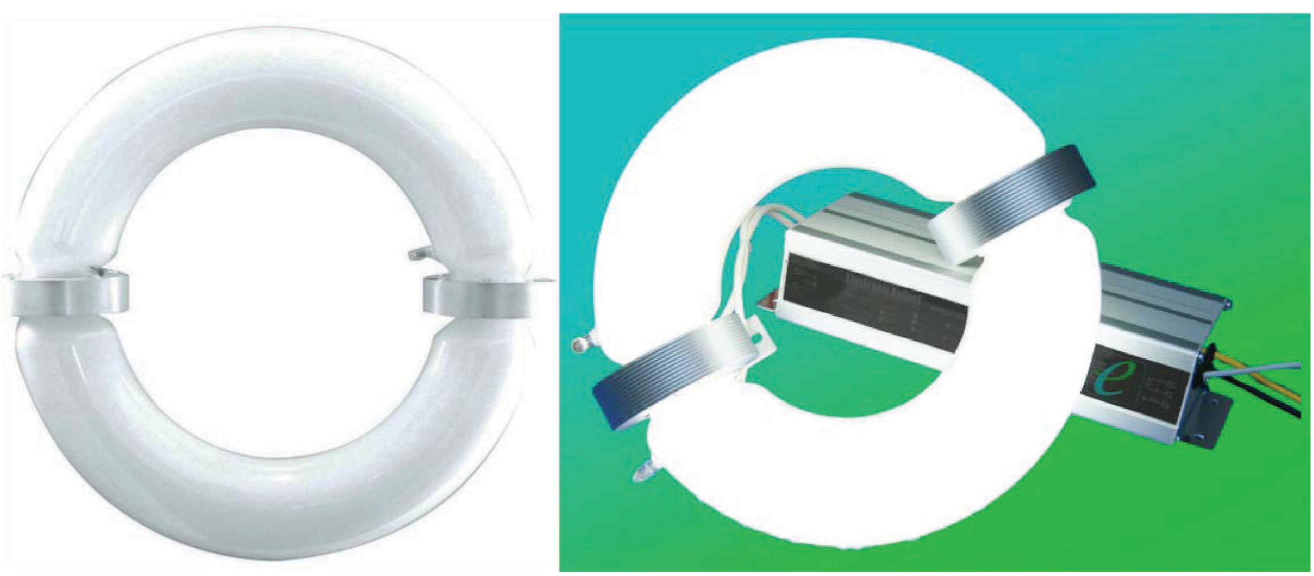

Figure 8. Example induction fluorescent lamps. Source: http://en.wikipedia.org/wiki/Electrodeless_lamp

Table 4. Lamp characteristics: induction fluorescent.

Lamp lumen/watt	63 to 84
System Efficacy lumen/watt	63 to 84
Rated Life (based on 50% mortality)	100,000 hrs
Rated Life (based on 70% lumen output)	60,000 hrs
Correlated Color Temperature (CCT)	3500K to 5000K
Color Rendering Index (CRI)	80

Multiple sources, compiled by Parsons Brinckerhoff

The performance metrics of typical IFL lamps used in parking garages are shown in Table 4.

Factors to be considered in the use of induction fluorescent lamps include:

Temperature: Starting temperatures for IFL lamps are quite low, ranging from −32°C (−25°F) to −40°C (−40°F), depending on lamp wattage. Lamp output does vary with temperature, but in a properly designed and enclosed fixture, IFL lamps are suitable for cold-weather operation. Amalgam tip covers are also available to provide faster warm-up under very cold operating conditions.

Lumen maintenance: The lumen depreciation of IFL lamps is fair, with the output declining to approximately 64% of rated lumens by the rated end of life, as shown in Figure 9. If the lamp life was rated in terms of L_{70} (the number of hours before the lamp output is expected to decline to 70% of rated lumens) like LED sources, the life would be rated at approximately 60,000 hours instead of 100,000 hours.

Fixture efficiencies: Because IFL lamps are large, they are generally not considered highly efficient in directing the lumens to the surfaces requiring lighting.

Controllability: IFL lamps are instant-on, requiring neither strike nor extended warm-up time. So, like FL lamps, they are amenable to controllers that turn the lamps on and off depending on daylight and the presence of patrons.

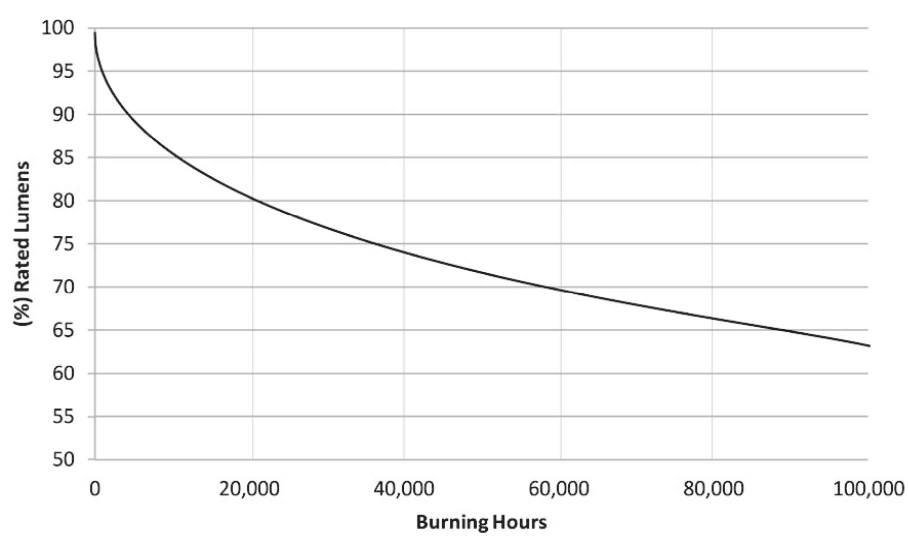

Figure 9. Lumen maintenance of typical induction fluorescent lamps. Source: Compiled by Parsons Brinckerhoff.

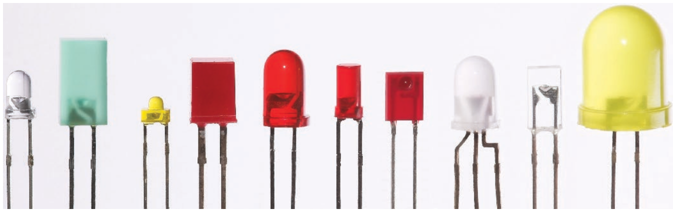

Figure 10. Example LEDs. Source: http://commons.wikimedia.org/wiki/File:Verschiedene_LEDs.jpg

2.5 Light-Emitting Diode (LED)

LEDs have made significant strides in recent years, becoming one of the strongest options for parking garage and lot lighting. LEDs are robust and have a long life, reducing maintenance costs. Single LEDs are small, allowing for excellent optical control, and the driver used to energize the LED is dimmable and digitally controllable. Each LED has relatively low light output and low power requirements. In lighting applications, single LEDs can be arrayed in bars, strips, or fields to provide efficient illumination. Example LEDs are shown in Figure 10.

LEDs have drawbacks, however, including sensitivity to heat, reduced efficacy when driven at operating current, and a high initial cost compared to other lamp types. Also, because individual LEDs are so small, they must be carefully combined with optics in a luminaire to prevent glare. Phosphor-based broadband LEDs have more blue output than other lamp types, but they have less output in the green spectrum, leading to color identification challenges. The U.S. Department of Energy (DOE) is funding research to address this "green hole" in the near term, so the problem might be solved two to four years after this guide is published.

LED technology is developing at a rapid pace; there are a large number of chip designs, and LEDs consume much less electricity than other lamp types. Performance metrics of LED luminaires typically used in a parking garage installation are shown in Table 5. The data are from CREE "Xlamp" LED series.

Factors to be considered in the use of LEDs include:

Temperature: LEDs decrease in lumen output as the semiconductor's temperature rises (junction temperature). LED lumen output ratings are based on 25°C (77°F), depending on the current energizing the LED. Exposure to heat not only reduces the output of an LED, but it also has a cumulative effect on an LED's lifetime. For example, a CREE XP-G LED is rated at 70% lumen output at 50,000 hours, if the junction temperature is less than 80°C (176°F), as shown in Figure 11. Above about 85°C (185°F), the lifetime drops sharply. Junction temperatures of >70°C (158°F) are not uncommon, so heat dissipation is a crucial part of LED circuit and luminaire design.

Table 5. Lamp characteristics: LED.

Lamp lumen/watt	100 to 140
System Efficacy lumen/watt	80 to 100
Rated Life (based on 70% light output)	100,000 hrs
Correlated Color Temperature (CCT)	3500K to 6000K
Color Rendering Index (CRI)	70 to 80

Source: CREE Xlamp technical specifications, compiled by Parsons Brinckerhoff

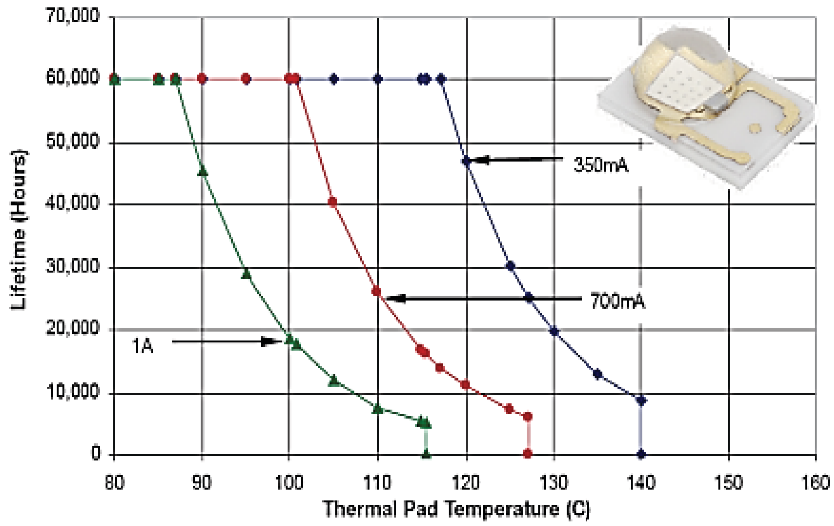

Figure 11. Example LED lifetime and junction temperature (range is from 176°F to 320°F). Source: Philips Lumileds technical specifications

Lumen maintenance: The lumen depreciation of an LED lamp is low. LED lamps maintain more than 95% of their lumens through the first 10,000 hours of operation, but depreciation increases at an accelerated pace after about 35,000 hours, depending on temperature and amperage.

Fixture efficiencies: Individual LEDs are directional and efficiently direct light away from the luminaire, unlike HID, FL, and IFL lamps, which are omnidirectional. Secondary optics have improved LED-lamp efficiency (85% to 95%) as well, because reflector design is very effective with point-source LEDs.

Controllability: LED sources are instant-on, requiring neither strike nor extended warm-up time.

Glare: LED sources have been found to be about twice as likely than other technologies to be identified as glaring. Therefore extra care should be taken to minimize the effect.

2.6 Organic Light-Emitting Diode (OLED)

OLEDs are flexible, transparent, and glare-free, allowing for a number of creative luminaire designs. OLED technology is ideal for decorative lighting and applications where light is integrated into the built environment. A possible garage application would be an array of OLED modules creating a luminous ceiling over a walkway. OLEDs are not well suited for parking garage applications, though, because they have very low efficiency and very high cost. An OLED example is shown in Figure 12.

OLED components will need to be integrated into luminaire design before they are useful for area lighting. Even though the layers of the substrate can be applied homogeneously to produce extremely uniform brightness, OLEDs are sensitive to water exposure. As a result, OLED luminaires used in exterior applications need to be encased in glass, increasing their veiling luminance.

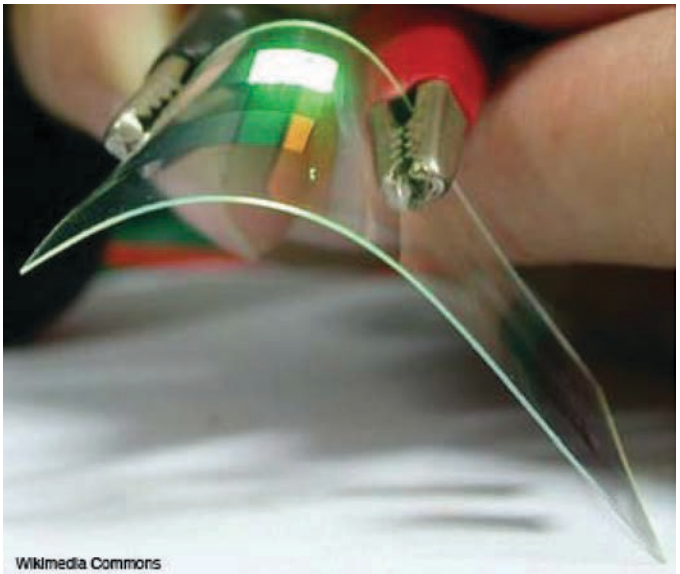

Figure 12. Example OLED lamp. Source: http://commons.wikimedia.org/wiki/File:OLED_EarlyProduct.JPG

Performance metrics of an OLED lamp are shown in Table 6. The data are from an OSRAM ORBEOS component and module.

Factors to be considered in the use of OLEDs include:

Temperature: OLED lifetime is a function of the operating temperature. For each 10°C rise above room temperature, an OLED loses 31% of its useful life. Because OLEDs are housed in clear flexible substrates, heat sinking is limited, and luminaires with OLEDs largely depend on natural air convection to maintain temperature.

Lumen maintenance: Light output is believed to be constant until the OLED fails.

Fixture efficiencies: OLED lighting is made up of large panels producing diffuse, uniform light; therefore, it is not highly efficient in directing the lamp lumens to the surfaces requiring lighting.

Controllability: OLEDs are instant-on. Dimming increases efficiency in both lumen output and life expectancy because it reduces an OLED panel's core temperature.

Table 6. Lamp characteristics: OLED.

Lamp lumen/watt	40 to 60
System Efficacy lumen/watt	23
Rated Life (based on 70% light output)	10,000 to 20,000 hrs
Correlated Color Temperature (CCT)	2900K to 3300K
Color Rendering Index (CRI)	>80

Source: OSRAM ORBEOS technical specifications, compiled by Parsons Brinckerhoff

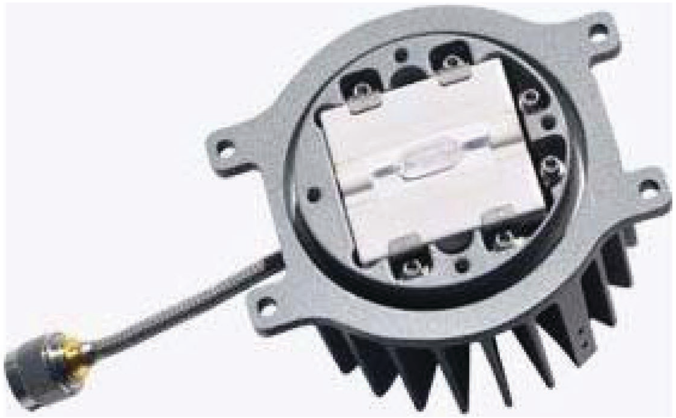

Figure 13. Example plasma lamp. Source: LUXIM.

2.7 Light Emitting Plasma (LEP)/Plasma Lamp

LEP lamps, also known as plasma lamps, have the longevity of LED lamps and the high efficacy of point-source optics. Unlike LEDs, plasma lamps are full-spectrum and do not require phosphor coatings. Used as grow-lights, high mast lights, and warehouse lighting, plasma lamps have a high lumen density (12,000 lm to 23,000 lm) and directional nature that may make them too bright and glaring for low-bay or parking garage luminaires. A plasma lamp is shown in Figure 13.

The chief advantage of an LEP lamp over an HID, FL, or IFL lamp is the LEP's highly directional "puck" that emits the light, improving fixture efficiency to as high as 90%. The full-spectrum output also provides increased mesopic/scotopic illuminance, greatly increasing nighttime visibility.

Various plasma lamp wattages are available from different manufacturers. Performance specifications for a plasma lamp likely to be used in a parking garage are shown in Table 7. Data are from a LUXIM 160W STA-25-03.

Factors to be considered in the use of LEP/plasma lamps include:

Temperature: At ambient operating temperatures above 45°C (113°F), driver reliability is reduced. At temperatures below –40°C (–40°F), start time is longer than is usually acceptable in a garage-lighting application.

Lumen maintenance: Light output is relatively steady, dimming throughout life with an LM_{70} of 50,000 hrs as shown in Figure 14.

Table 7. Lamp characteristics: LEP/plasma lamp.

Lamp lumen/watt	75
System Efficacy lumen/watt	75
Rated Life (based on 70% light output)	50,000 hrs
Correlated Color Temperature (CCT)	5200K
Color Rendering Index (CRI)	75

Source: Data from LUXIM 160W STA-25-03 technical specifications, compiled by Parsons Brinckerhoff

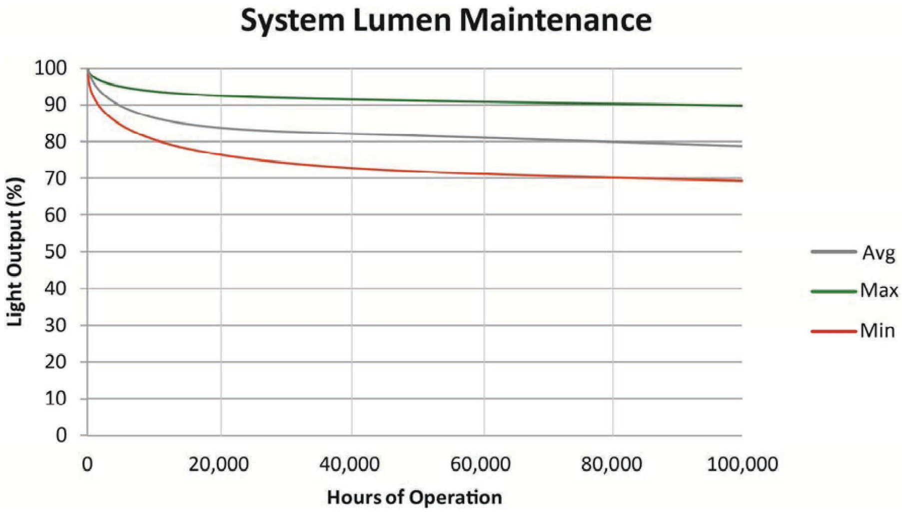

Figure 14. Lumen maintenance of typical plasma lamp. Source: Compiled by Parsons Brinckerhoff.

Fixture efficiencies: Because plasma lamps are highly directional, they have optimal light distribution with minimal loss.

Controllability: Start time at 25°C (77°F) is 30 seconds. The lamp does not need to cool down, and restrike is also 30 seconds.

2.8 Lamp Technology Summary

A summary of the light source and luminaire technologies is shown in Table 8.

Table 8. Summary of light source characteristics.

SOURCE COMPARISON SUMMARY						
	Lm/W - Source	**Lm/W - System**	**Life - 70% lumen output (LM_{70})**	**Color Temp.**	**Color Rendering Index**	**System Cost - Relative**
FL	97	85–98	40,000 hr	3000K–6500K	81–85	$
IFL	63–84	63–84	60,000 hr	3500K–5000K	80	$$$
HPS	80–125	61–107	30,000 hr	1900K–2100K	22	$$
MH	105–120	100–111	24,000 hr	3000K–4200K	90	$$
LED	100–140	80–100	100,000 hr	3500K–6000K	70–80	$$$
OLED	40–60	23	10,000 hr–20,000 hr	2900K–3300K	>80	N/A
LEP	75	75	50,000 hr	5200K	75–95	N/A

Source: LUXIM, CREE, Osram-Sylvania, and Philips technical specifications, compiled by Parsons Brinckerhoff

CHAPTER 3

Designing for Lighting Performance

There are several sources of recommendations and guidelines for lighting design and evaluation. The *IES Lighting Handbook*, 10th Edition, provides lighting requirements for a parking garage. Similarly, IES RP-20, "Recommended Practice for Parking Facilities," provides additional information for the designer in terms of lighting levels and maintenance. The IES G-1, "Guideline for Security Lighting," contains more information relevant to garage lighting. The newer IES *Lighting Handbook*, discussed below, covers parking garage lighting as well. None of these documents, however, is specific to airport parking garages. This guidebook chapter covers some of the existing guidelines, their application to airport parking garages, current lighting practices, airport garage user feedback on garage lighting, and some methodologies for determining the lighting needs in airport parking garages. It also gives recommendations for airport garage lighting stemming from existing standards and the state of the industry.

3.1 Design Standards

3.1.1 IESNA RP-20

The IES recommends practices for lighting various types of spaces; the 1998 *IES Recommended Practice for Lighting of Parking Facilities* (RP-20) provides guidance on the required lighting levels for parking garages. IESNA RP-20 highlights the potential for vehicle-to-pedestrian conflict, the need for security, and the importance of the entrance and exit ramps as the basis of its lighting design recommendations. These recommendations, taken from Table 2 of RP-20, are shown here in Table 9.

The IESNA RP-20 recommendations cover horizontal and vertical luminance. IESNA RP-20 also recommends using daylighting to achieve the higher light levels required at the entrance and exits to the garage. It recommends uniformity levels, defined as the ratio of maximum light level to the minimum light level. It also covers highlighting special areas in the garage with different lighting levels, and different lighting for entrances during the night and day to aid in transitioning. Illuminance, luminance, uniformity, and highlighting will be covered in more detail in the next subsection.

3.1.2 IES Lighting Handbook

A more recent publication by the IES, the *Lighting Handbook* (DiLaura et al., 2011), provides guidance for lighting parking garages beyond that in the IESNA RP-20.

The *Lighting Handbook* guidance establishes the horizontal and vertical illuminance criteria based on tasks in the space. While specific values are not provided, the *Lighting Handbook*

Table 9. Recommended lighting design values in parking garages.

Garage Section	Recommended Minimum Vertical Illuminance (lx)	Recommended Minimum Horizontal Illuminance (lx)	Recommended Minimum Uniformity Ratio of Horizontal Illuminance (Maximum lx:Minimum lx)
Basic	5	10	10:1
Ramps – Day	10	20	10:1
Ramps – Night	5	10	10:1
Entrances – Day	250	500	
Entrances – Night	5	10	10:1
Stairways	10	20	

Source: Data from IESNA RP-20, 1998, Table 2, compiled by VTTI

recommends that garage designers should make illuminance selections based on the following steps:

- Create a system for determining which areas have lighting with what illuminance level. Section 4.12 of the *Lighting Handbook* suggests designers categorize the space based on lighting need, with Category A for 1 lx, up to Category K, for 50 lx.
- Link each activity with an illuminance category. Activities may be associated with the different locations within the parking area, such as ramps and elevators, or they could be based on a task survey.
- Evaluate observers' ages. Three categories of age are considered in the *Lighting Handbook:* (1) at least 50% of the observers are less than 25 years old, (2) 50% of observers are between 25 and 65, and (3) at least 50% of the observers are above 65. Because light perception changes with age, the age categories are associated with illuminance target values; Category 1 has the lowest target value, and Category 3 has the highest.
- Determine the appropriate horizontal and vertical illuminance target values. Different areas, activities, and age groups will require different horizontal and vertical illuminances.
- Determine the design metrics, including average, minimum, and maximum, as well as uniformities. Average-to-minimum and maximum-to-minimum present the lower bound and upper bound for illuminance uniformities. The upper limit for parking decks should not exceed 10-to-1.
- Account for mesopic multipliers (discussed later in this document) to ensure they are appropriate. The mesopic adaptation state should be assessed to determine if observers are likely to experience it. After obtaining the multipliers, adjust the illuminance criteria. A detailed example can be found at Table 26.6 in the *Lighting Handbook.*
- Finalize recommended nighttime and daytime illuminance. Itemize nighttime and daytime horizontal and vertical illuminance as well as uniformity criteria. In general, nighttime illuminances, the baseline illuminance condition, are consistent for different locations such as drive aisles, parking bays, ramps, and entries. Daytime illuminances are consistent with the baseline condition only for drive aisles and parking bays. Ramps and corners should be designed to have illuminance of two times the baseline condition. Entries and exits require illuminance of 10 times the baseline condition.

Finally, the *Lighting Handbook* provides guidance on accent lighting. Parking garage users are interested in finding some locations, such as elevators and stairs, very easily, and accent lighting can help. Table 15.2 in the *Lighting Handbook* (DiLaura et al., 2011) can help define accenting criteria. Current practice in airport garage lighting follows this suggestion. In many cases, 10× lighting is used to highlight important areas in airport garages, but inefficient incandescent luminaires are often used, which presents an opportunity for lighting designers to reduce operating costs.

The IES *Lighting Handbook* is a complicated document that requires significant cross-referencing with cumbersome criteria. The next IES RP-20 is expected to incorporate guidelines similar to those in the *Lighting Handbook;* however, the guidelines will be simplified and clarified for ease of use.

3.1.3 APTA Recommended Practices

Another source of recommendations for parking garage lighting is the APTA Recommended Practice for Security Lighting for Transit Passenger Facilities (APTA, 2009). APTA recommends continuous lighting for parking garages. Its recommendations for lighting levels are shown in Table 10 here, taken from tables 6 and 7 in the APTA document.

APTA recommends significantly higher lighting levels than the IES RP-20 (about 60 lx versus 10). The APTA document does not provide additional recommendations for lighting in special areas or enhanced work spaces. The APTA document referenced patron safety and security; that is likely the reason their document has higher recommended lighting levels than the RP-20.

3.1.4 City Codes

In addition to the recommended lighting criteria, some local authorities provide regulations for parking garage lighting. For example, the City of Santa Barbara, California, regulates garage-lighting design to enhance the lighting quality and energy use. The regulations also reduce the potential for light pollution, glare, light trespass, and wasted energy caused by deficient lighting design and misdirected light (SOTCOSB, 2009).

The following goals and guidelines are excerpted from the Santa Barbara regulation:

Goals

- A safe transition from garage interior to the exterior area and vice versa during both daytime and nighttime is required.
- Minimum lighting for safety, security, and uniformity must be provided. Higher lighting levels may be approved by the Design Review Boards for additional safety and security.
- Selection of fixture type, lighting technology, location, and control of lighting level should be conducted in a way to optimize energy consumption.

Table 10. Recommended lighting design values in parking garages.

Garage Section	Minimum Recommended Illuminance (lx)				Averaged Recommended Illuminance (lx)	
	Horizontal Maintained	Vertical Maintained	Horizontal Initial	Vertical Initial	Maintained	Initial
Open parking lots	11	5.4	15	7.5	32	46
Parking garages	16	8.6	24	13	65	97

Source: Data from APTA Recommended Practice for Security Lighting for Transit Passenger Facilities, 2009, Table 7, compiled by VTTI

- Title 24 Lighting Standards need to be met. [Title 24 is an energy regulation specific to California].

Guidelines

- Acceptable lighting technologies that meet the guidelines are HPS and fluorescent. Deluxe HPS lamps are also recommended because of their high color rendering ability. MH lighting is not recommended and is not permitted in the transition section or on roof-level pole-top fixtures. LED and induction lighting may be eligible where warm color quality is desired.
- Transition sections, for both drivers and pedestrians, must extend 60 ft into the building from its exterior face. Illuminance at the transition sections must be controlled according to the difference between the lighting level of the interior and the exterior, which varies by the time of day; sunlight, moonlight, and street lighting all affect the exterior illuminance.
- The brightness of the garage interior must be evaluated. Directed task lighting is preferred over higher general illumination.
- Glare from directly viewing the light sources can be an issue when the light sources are visible from outside the building, so fixtures must then be carefully placed and/or shielded.
- On roof parking levels, pole-top fixtures should be cutoff fixtures. Other factors to be considered are minimizing pole height and avoiding placing the poles at the perimeter of the building.
- Metal halide lighting is not recommended, but if used in the garage interior, the color of the walls should warm the reflected light.
- When using HID lighting, cutoff fixtures with horizontal lamp mounting and flat glass lenses are preferred. "Sag" or "drop" lenses are not allowed because they lead to excessive glare.
- For better energy conservation, additional lighting controls for garage interior lighting are recommended to control the lighting according to need.
- Average horizontal illuminance at ground level should be aimed at one foot-candle (fc) and should not exceed 1.5 fc. Where needed and approved by the Design Review Boards, higher values can be approved for additional safety and security.
- A foot-candle plot that illustrates illuminance levels at the transition zones, up to the furthest floor area visible from the vehicle entrance or exit, must be presented. Minimum, average, and maximum foot-candles and the uniformity ratio must be calculated. Illuminance should not be more than the ambient street lighting level at 10 ft beyond the vehicle entrance or exit.
- Sufficient plan, detail, section, and finish information need to be included in plans submitted to the Design Review Board, so they can determine whether or not the plans adhere to the guidelines.

These guidelines include a plan-review checklist to facilitate lighting design meeting the requirements.

3.2 Lighting Standards and Recommendations for Airport Garages

The following guidance was developed assuming a medium dark concrete surface. Adjustments will need to be made for different pavement surfaces as recommended in the Building Design Considerations chapter.

3.2.1 Illuminance Level

Horizontal illuminance. The authors of this guide found that airport garages tend to have higher average horizontal illuminances than the values suggested by RP-20, ranging from 30–100 lx in the interior parking levels, whereas the minimum levels suggested by RP-20 are 10 lx for basic areas and bays at night, and 20 lx for ramps and stairways. Since these are

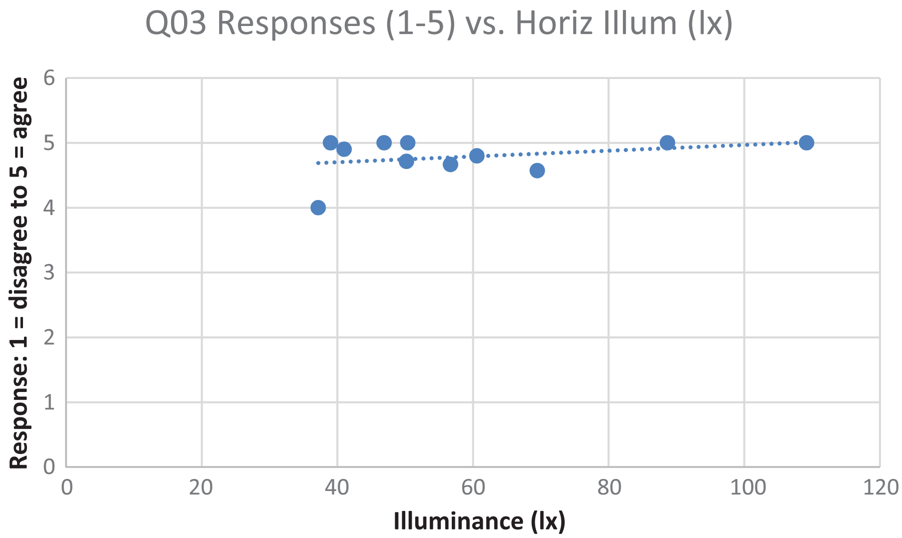

Figure 15. Q03—feeling of comfort at horizontal illuminance levels. Source: VTTI Analysis.

the minimums, an assumption needs to be made about uniformity to determine the average values suggested by RP-20. If one assumes 2:1 uniformity, which would be difficult to achieve in practice for reasonable cost, then the maximum illuminance would be 20 lx and the average would be 15 lx. With a maximum uniformity ratio of 10:1, the average rises to 55 lx. Therefore, current practice is to illuminate at a horizontal illuminance approximately two times RP-20.

The higher levels of illumination could be because lighting design for airport garages is more security-focused than that for other garage types. Discussions with some personnel involved in airport garage lighting indicated that the higher lighting levels were driven by a concern for patron safety. Additionally, a survey of airport garage patrons found that they agree that they begin to feel comfortable (Figure 15) and safe (Figure 16) beginning at an average horizontal illuminance of ~35 lx; and strongly agree that they feel comfortable and safe by 40 lx, while not

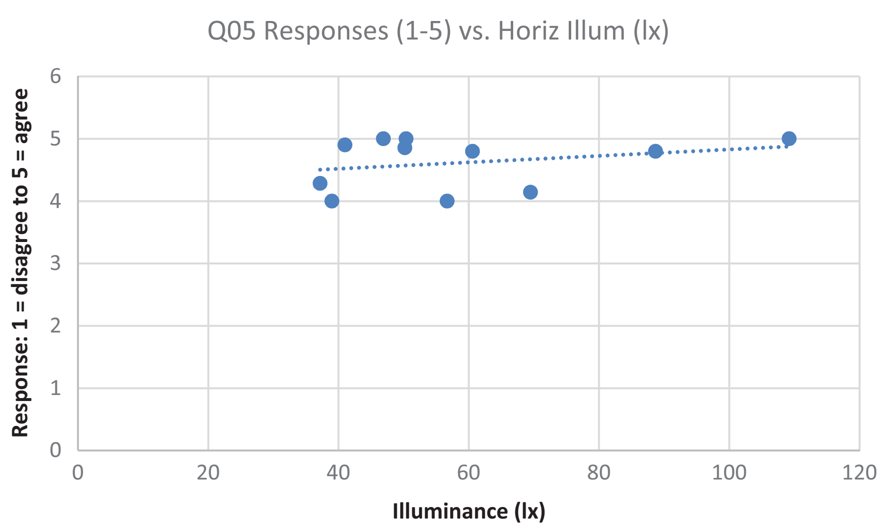

Figure 16. Q05—feeling safe at horizontal illuminance levels. Source: VTTI Analysis.

experiencing significant glare. However, beyond an average vertical illuminance of 40 lx, there is little increase in comfort or feeling of safety.

These data do not determine how little average horizontal illuminance is needed for a neutral or negative response to either feeling safe or comfortable.

The conclusion drawn here is that the RP-20 guidelines may not be ideal for airport garages. For safety and security, an average horizontal illuminance of 40 lx is recommended for general (not highlighted) airport garage areas.

Recommendation: Airport garage bays and general areas should have a minimum average horizontal illuminance of 40 lx to maximize patron comfort without expending excess capital, equipment, or power.

Vertical illuminance. Vertical illuminance recommendations are directed at pedestrian safety because it highlights vertical surfaces and helps drivers detect and recognize pedestrians. The RP-20 guidelines for vertical illuminance are 5 lx in general areas at night, and 10 lx in stairways. This is about half of the recommended horizontal illuminance. In practice, average vertical illuminance levels found in airport garages were higher, roughly proportional to the horizontal illuminance. However, it was found that vertical illuminance was less critical than horizontal illuminance when it comes to patron comfort and safety (Figure 17). Therefore, a minimum average vertical illuminance is not required.

Vertical-to-horizontal illuminance ratio. The RP-20 guidelines recommend a vertical-to-horizontal illuminance ratio of 1:2. In practice, airport garages tend to have lower vertical-to-horizontal illuminance ratios. In many garages, the ratio was closer to 1:1. This may be because airport garage lighting designs use fewer wider-angle luminaires to reduce installation and capital costs. High vertical illumination levels can cause glare, and luminaire spacing with a large offset can exacerbate the problem of shadows near vehicles. Research shows that there appears to be a correlation between the illuminance ratio and perceived glare (Figure 18) and that most of the LED lamps were perceived as more glaring than other lighting technologies at the same ratios.

The two outliers and the one other marked data point are LED installations. As described in the technology section, LED sources are very small and utilize different optics for spreading the light out, resulting in a higher chance of glare. See the section on glare later in this chapter.

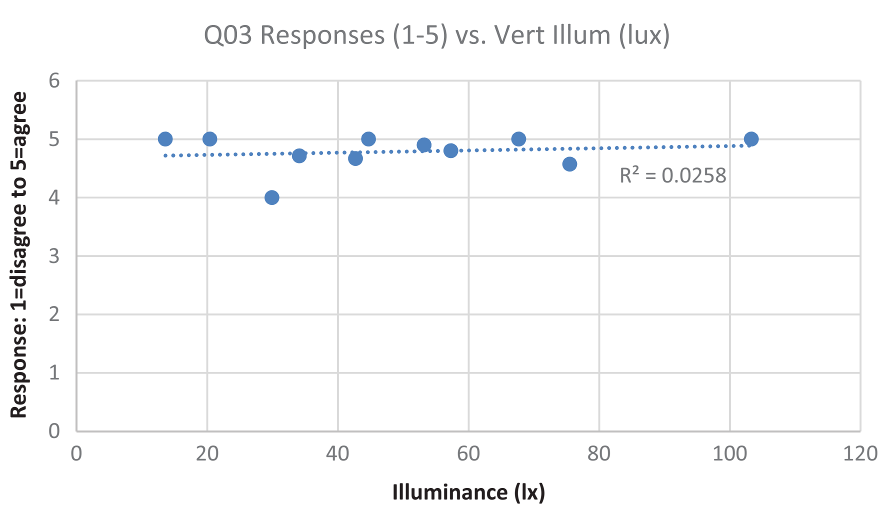

Figure 17. Feelings of comfort at vertical illuminance levels. Source: VTTI Analysis.

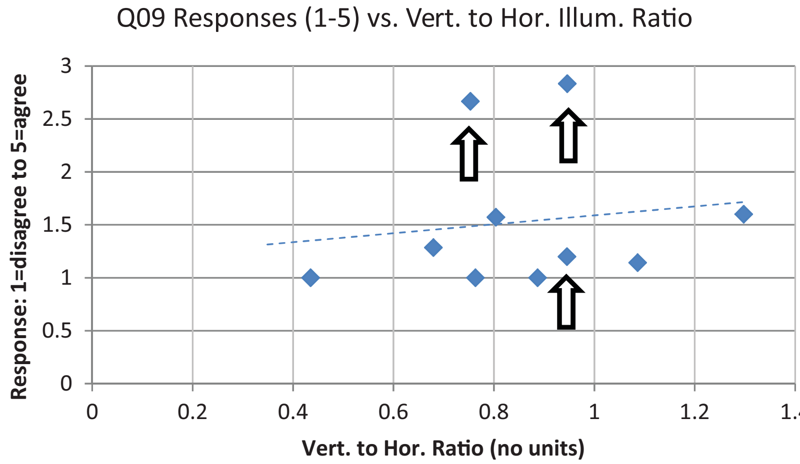

Figure 18. Glare response versus ratio of horizontal illuminance to vertical illuminance. The blue line is the trend of glare assessment. The marked data points are LED sources. Source: VTTI Analysis.

Recommendation: Airport garage lighting should strive for 1:2 vertical-to-horizontal illuminance ratio from RP-20, but LED installations should strive for 1:3–1:2 vertical-to-horizontal illuminance ratio.

These illuminance recommendations are for general areas. Recommendations for highlighted areas within an airport garage, like ramps, toll areas, entrances and exits, and cross walks are covered in a subsequent section.

3.2.2 Emergency Lighting

According to RP-20, if there is a power outage, a low-level lighting system is required to provide safety and security in the parking facility. The emergency lighting system should provide 10% of the light of the normal system, and at least 10 lx along the path of egress. This lighting system should meet the requirements of National Fire Protection Association (NFPA) 101 Life Safety Code and the emergency system requirements of NFPA 70 National Electrical Code.

IES RP-20 does not specifically mention airports or activities that might require special attention during the lighting design process. Airport garage safety requirements mirror those of other garage types, so the RP-20 guidelines are recommended.

Recommendation: Emergency lighting should provide 10% of the lighting level of the regular garage lighting system and provide 10 lx along the paths of egress.

3.2.3 Luminance

Luminance, the light reflected from surfaces, drives roadway visibility. Luminance depends both on illuminance level and the reflectivity of the road surface.

Common standards (RP-8, RP-20, the *Lighting Handbook*) list reflectance values or rules of thumb. In general, darker pavement requires more lighting. Painting a surface can increase its luminance by increasing its reflectivity, but glossy paints can be so reflective that they cause glare. Painted surfaces require maintenance, and paint on road surfaces requires maintenance on a short timeline, possibly annually. One solution is to stain concrete with a color that will reflect light in the amount and wavelength (i.e., warm, cool) desired. From the *Lighting Handbook:*

> Surface reflectances and accenting: Specific light reflectance values (LRVs) are recommended for columns, walls, and ceilings (particularly adjacent to the ramps, corners, entries, and exits) with and without color accent as a guiding tool. As a result, luminances and overall perception can be improved. High LRVs result in improved vertical and horizontal illuminance, reduced glare, better user perception, and other benefits.

Recommendation: When designing and upgrading lighting systems for airport garages, take into account the effect of the color and material of the walls and road on luminance and color temperature.

3.2.4 Uniformity

This metric, expressed as the average:minimum illuminance ratio or the maximum:minimum illuminance ratio, is used to quantify the impact of areas with minimal light levels, such as dark shadows between vehicles in airport garages. Low uniformity can indicate both uncomfortably bright and awkwardly dim areas. When light is very uniform, however, few shadows are cast, reducing the contrast of a vertically illuminated object or pedestrian. Thus, high uniformity (low contrast) can hinder detection and recognition. A survey of airport garage patrons found little link between lighting uniformity and patron comfort, so it is possible that if lighting uniformity is between the above extremes, the effect of lighting on patron experience is small.

Most airport garages have continuously high vehicle occupancy. A significant portion of those vehicles is tall sport-utility vehicles (SUVs) and pickup trucks. Those vehicles cast dark shadows that have a significant effect on minimum light levels, especially in-between vehicles (see Figure 19). Even if garage lighting guidelines are met, the light level near vehicles can dip below 1 lx. When these low levels are compared to the average or peak values, the uniformity ratios are considerably higher than those suggested by RP-20 (10:1 maximum:minimum horizontal illuminance levels). Airport garage lighting design should take into consideration shadows produced by a garage full of tall vehicles and strive to provide minimum recommended lighting levels between vehicles.

Recommendation: Follow the RP-20 guidelines for minimum horizontal uniformity (i.e., 10:1 maximum:minimum), but take the presence of parked SUVs into account.

Figure 19. Shadows cast by tall SUVs. Source: VTTI.

3.2.5 Color Contrast

Recent studies suggest that color contrast is, like vertical illuminance, important for facial recognition and object detection. Surveys performed by the authors suggest that uniformity is important for color recognition. At this time, no recommendations stem from this exploratory research.

3.2.6 Airport Garage Layout and Highlighting

The effectiveness of parking garage lighting depends on the activities performed in the various areas of the garage. Locations with more pedestrian traffic, rental vehicles, and toll booths can be made brighter than surrounding areas to promote safety. Lighting can also be used to help guide users toward their destination, usually walkways, stairways, payment areas, airport entrance, vehicle rental, or the garage exit. Entrances and exits should have transitional lighting to prevent glare when moving into and out of the garage. Other areas can be lit to a lesser extent, saving energy. Airport garages share similarities and differences with typical garages, affecting the lighting design recommendations here.

Many garages have the following areas:

- Dedicated corners/ramps;
- Drive aisles/parking areas;
- Drop-off/pickup areas, interior vehicle transaction areas, and valet;
- Elevator lobbies, pedestrian transaction area, and stairways; and
- Vehicular entries and exits.

Airport parking garages tend to have the following less-common areas:

- Vehicle rental offices;
- Baggage cart rental; and
- Higher-security areas.

In addition, airport parking garages tend to not be located near residential areas.

Areas with pedestrian traffic. The RP-20 acknowledges the importance of highlighting stairways in a garage; while it recommends a basic horizontal illuminance of 10 lx at night, it recommends 20 lx for stairways. This is to prevent tripping, and for security.

Walkways through a parking garage have different illumination requirements than those of stairways. While security and tripping are both concerns in walkways, so is making sure drivers can see pedestrians. Illuminance measurements at airport garages found huge variation in the ratio of walkway illumination to the illumination in the parking bay. In one garage, that ratio was 30:1 for horizontal illuminance and about 12:1 for vertical illuminance. In two other garages, the ratio of walkway illumination to the illumination in a nearby parking bay was between 1.5:1 and 2:1 for both horizontal and vertical illuminance. The amount of glare depends heavily on the luminaire cutoff, possibly explaining the lack of perceived glare in the garage with a 30:1 highlighting ratio. Cutoff can be creatively accomplished with a number of devices, including the garage's structural beams.

Airport patrons, on average, agreed that they felt safe and comfortable to nearly the same extent in the above garages. They also agreed that none of the above garages had glaring lighting. Those data suggest that the highlighting ratio, between 2:1 and 10:1 or higher with cutoff, does not affect perceptions of safety or glare. The recommendation here is to follow the spirit of RP-20 with respect to highlighting walkways.

Recommendation: Highlight walkways and other areas with high pedestrian traffic at a ratio of at least 2:1 with respect to the basic lighting level in the garage. At ratios of above 10:1, use cutoff to prevent glare. Make sure vertical illuminance does not fall below 20 lx.

Vehicle rental areas. Drivers likely unfamiliar with their vehicles and surroundings, as well as pedestrians, will be near vehicle rental offices. These areas should also be highlighted.

Recommendation: Highlight vehicle rental areas at a ratio of 2:1 with respect to the basic lighting level in the garage.

Ramps. Depending on the garage layout, ramps may have low sight distance and pedestrian traffic. The RP-20 suggests that, during the day, ramps be illuminated two times as brightly as the basic level in the garage. Bi-level lighting could be used on ramps to reduce costs during the night.

Recommendation: Highlight ramps at a ratio of 2:1 with respect to the basic lighting level recommended in this guidebook in the garage during the day and utilize bi-level lighting at night if cost-effective.

Entrances. Entrances are transition zones, and are not unique to airport garages. It is suggested designers of airport garage lighting follow the RP-20 recommendations for lighting entrance areas. See Table 9.

Recommendation: Follow the recommendations in RP-20 for lighting airport garage entrances.

Top level. The rooftop spaces on parking garages are lighted in accordance with the parking lot standard in RP-20, 2 lx for basic horizontal illuminance, and 5 lx for enhanced security. Having the horizontal illuminance on the top level match that on the other levels (recommended 40 lx) would provide a sense of continuity between levels, and could increase patrons' feelings of safety and encourage usage of the upper decks.

Recommendation: Illuminate the top level of the garage to the same level as the basic lighting in the parking bays.

3.2.7 Daylighting

Like other garages, airport parking garages should take advantage of fractional daylighting and controlled lighting. The extent to which daylighting is possible largely depends on the garage's layout, and more details about daylighting design strategies can be found in section 11.3.2.4 of the *Lighting Handbook*. This guide recommends daylight survey in the peripheral bays and drive lanes, as nine out of 11 peripheral airport bays surveyed had enough daylight illumination to meet RP-20 and the general recommended illumination levels in this guide (up to 50 feet from the perimeter). Daylight lighting can reach much farther, as much as three bays in from the perimeter, which is over 150 feet. Therefore, there is significant savings potential related to using bi-level lighting with daylight sensors in at least the outermost bays and drive lanes.

Recommendation: Survey the outer bays and drive lanes for daylighting and to determine if daylight sensors and bi-level lighting can be used. Follow the design strategies outlined in the *Lighting Handbook* for daylighting in airport garages.

3.2.8 Luminaire Efficacy

Efficacy is the main measure of the light produced by, and the efficiency of, a luminaire. A luminaire's optics and reflectors significantly impact how much light it produces. Efficacy is usually calculated and reported as light loss factor (LLF).

The LLF value is applied as a multiplier to achieve the maintained lighting level from the initial installed level. From ANSI/IES RP-8-00 (American National Standard Practice for Roadway Lighting):

$$LLF = LLD \times LDD \times LATF \times LCD \times HE \times VE \times BF$$

where:

- LLD is lamp lumen depreciation and is fixed by lamp type; for example, LEDs have an LLD of 0.70;
- LDD is luminaire dirt depreciation and depends on installation environment (see Figure 20);
- LATF is luminaire ambient temperature effects and differs by lamp type and local temperatures;
- LCD is luminaire component depreciation;
- HE is a heat extraction factor;
- VE is voltage effects such as transients; and
- BF is the driver and lamp factor (Ballast Factors) and includes loss of efficiency when operating at off specification conditions.

LLF affects cost considerations in the lighting design. For example, if the luminaires in one design have a 5% higher LLF than those in another design, the first design would require 5% more initial equipment, 5% more energy to operate, and 5% more spending on maintenance. The LLF's impact on project cost can mean the difference between new technology insertion and continued use of legacy systems at higher energy costs. Figure 20 provides some guidance for LLF estimation, as LDD is a major component of LLF.

Complicating LLF calculations is the fact that the LDD is often assumed to be equal across the luminaire output, when that is not the case. Luminaire testing found that dirt depreciation is more significant at the edges of the area of distributed light than it is directly under the luminaire, because low angles are more affected by dirt on the luminaire's glass (the luminaire tested was a flat-lensed II

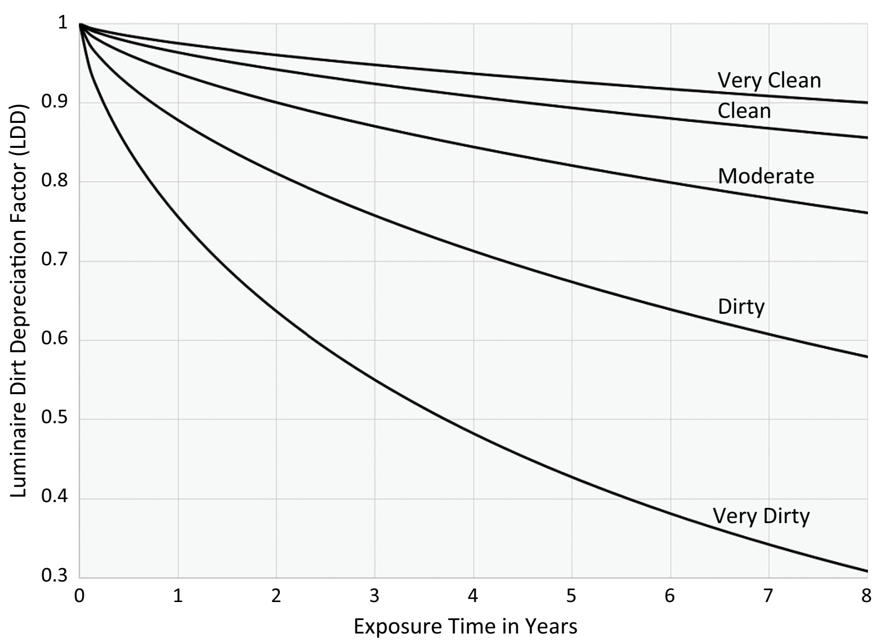

Figure 20. Example chart for finding LDD based on time and environment (not for use in lighting design; for design, reference IES RP-08-00). Source: VTTI Analysis.

medium-throw luminaire). The testing showed that assuming a single dirt depreciation factor applies equally across the entire area of a luminaire's light distribution is fundamentally incorrect.

Recommendation: Light loss factors should be calculated for airport garage lighting designs, with special attention to dirt depreciation.

3.2.9 Glare

Glare, or light that is so bright that it causes discomfort or impairs one's ability to make out surrounding objects, impedes wayfinding and increases the chances of pedestrian-vehicle conflict. In parking garages, drivers and pedestrians experience glare differently. Drivers are usually lower than pedestrians. Because drivers are lower than pedestrians, and because the vehicle roofs cut off light, for seated drivers to see the same light source as pedestrians, the drivers would have to be farther away from the light source. Therefore, glare is more of an issue for pedestrians in parking garages than it is for drivers, except in areas with high illumination such as entrances and ramps.

A number of design constraints can introduce glare into a parking garage's lighting. Those constraints are related to the parking garage environment, with low ceilings, helix ramps, sunlight intrusion, and the size of a lamp.

As illustrated in the discussion of vertical-to-horizontal illuminance ratio, a smaller ratio of vertical-to-horizontal illuminance and location of the luminaires to utilize the garage structure as vertical cutoffs can reduce the perception of glare.

Ceiling height. High capital costs tend to drive garage-lighting designers towards using fewer luminaires with a larger area of illuminance. These large-area luminaires, when mounted on typically low (7 to 9 ft) garage ceilings, throw bright light out at a shallow angle, causing glare. Therefore, glare can be a significant challenge when balancing the number of luminaires, light distribution, and cost.

Recommendation: Place a great value on reducing glare in airport garages because the potential for pedestrian-vehicle conflict is high.

Helix ramps. Second, helix ramps are often illuminated more brightly than the surrounding garage areas. That, combined with a lack of space, means many helix ramps have luminaires on their inner walls aimed in the direction of travel. The luminaires usually do not produce glare in the drivers' line of sight, but they can produce glare in peripheral vision.

Recommendation: On helix ramps, place luminaires above vehicle level so the vehicle roof will cut off the light, or carefully shield the luminaires.

Sunlight intrusion. Open sidewalls in aboveground garages allow sunlight in at various times of day. Depending on the garage layout and time of day, sunlight can cause more glare than artificial lighting, especially for those in the darker interior of the garage. To alleviate sunlight glare, airport garage lighting can have higher illuminance in the bays close to the edges of the garage to help patrons transition between sunlight and interior lighting. Designers could also place light-blocking or diffusing sidewalls on the east and west faces of the garage.

Recommendation: Evaluate the parking garage site for sunlight intrusion. Consider the location of walkways, orientation of the garage walls, time of day, and interior illumination levels. Raise interior illuminance or block sunlight if necessary.

Daylighting can be helpful if utilized correctly; see Chapter 4: Building Design Considerations.

Light-source size. Some light sources, like LEDs, are very small, and appear more glaring than larger lamps with the same intensity. As illustrated in the vertical-to-horizontal illuminance ratio section above, LED light sources are more likely to be perceived as glaring.

The unified glare rating, or UGR (CIE 117-1995—Discomfort Glare in Interior Lighting), is based on the background luminance (L_B), fixture luminance (L), and the solid angle subtended by the light source (ω) and the Guth position index. The Guth position index is based on two angles: α = angle from vertical of the plane containing the source and the line of sight in degrees; and β = angle between the line of sight and the line from the observer to the source. This produces UGR values that range from 5 to 40, where anything at 10 or below is negligible and anything above 30 is unacceptably glaring. The UGR is proportional to the log (L^2/L_B) indicating that higher background luminance will reduce glare. Luminance is also by definition, intensity of light emitted per unit area; so a larger light source, i.e., a larger solid angle, will also have a lower luminance (L) for a given total output in lumens.

Unfortunately, UGR is generally known to only be accurate for certain source sizes. It is limited to source sizes between 0.0003 steradians and 0.1 steradians. This minimum corresponds approximately to the minimum of a 2-inch source (such as a standard incandescent bulb) from about 32 feet away, which is much larger than an LED source in a luminaire, so cannot be accurately used on LED sources.

Recommendation: When using luminaires with small light sources, carefully choose the optics to reduce luminance of the source, and use cutoff and background luminance to reduce glare.

Creative cutoff. Designers should use existing features to cut off potentially glaring light sources as a way to cut costs. Luminaires can be placed next to beams or other structures in the garage, cutting off the light and shielding an area from potential glare. To improve efficacy, the structure used as the cutoff should be painted or stained white to reflect as much light as possible. When reducing the glare to drivers, the driver's height and average vehicle roof height should also be considered.

Recommendation: Consider glare with respect to both drivers and pedestrians. Use the parking garage environment to creatively and cost-effectively cut off light and prevent glare.

3.2.10 Light Trespass

Airport garages are usually located away from residences, but close to hotels and restaurants. Light trespass from an airport garage is less likely to aggravate residents, but it is more likely to aggravate travelers, potentially driving them away from the airport and businesses housed therein.

There are three main concerns for light trespass with respect to airport garages: the lighting on the top level, lighting trespass from the ramps, and the lighting at the edges of the parking floors.

Lighting on the top level. On the top levels of parking garages, luminaires are usually placed at 25 feet, because higher placement allows for less complicated luminaires and optics and lower cost. Depending upon the luminaire type and placement, significant light could trespass past the edge of the garage; thus trespass considerations must be balanced with cost effectiveness and achieving good uniformity and illuminance levels.

Recommendation: Adjust luminaire placement and cutoff design to prevent light trespass on airport garage top levels.

Ramp and helix illumination. Ramps and entrances should be more brightly illuminated than other garage areas, so light trespass from these areas is more likely. In addition, external ramps, especially helix ramps, usually have minimal clearance above and to the side of the vehicles, forcing designers to place luminaires on the sidewalls, shining outward. If the helix has an open outer wall, a significant amount of light could project out of the helix at a low angle.

Recommendation: On a helix ramp, either place the luminaire close to the ceiling, or raise the outer wall to prevent light trespass.

Perimeter lighting of each floor. The luminaires nearest to the perimeter of the garage can create light trespass through open sidewalls. Light designers have a few options to avoid this. Luminaires with asymmetric illuminance patterns could be located near the wall and aimed toward the center of the garage. This way, any trespass light will be exiting at an angle near vertical, illuminating the base of the garage only. Another option would be to install light shields or additional reflectors to prevent trespass. Finally, the structure of the garage can be used to provide additional cutoff as mentioned in the glare section above.

Recommendation: Use the garage structure, luminaires with asymmetric illuminance patterns, and light shields to prevent light trespass around the edges of the garage.

CHAPTER 4

Building Design Considerations

4.1 Site Planning

4.1.1 Orientation on the Site

It is unlikely that the lighting design will have control over the orientation of the garage on the site. This is usually driven by the site topography and available space after siting of the terminals and runways, etc. However, should there be some opportunity for siting, the lighting design should strive to take advantage of daylighting as described in the next section. In addition, from a photometric perspective, siting of the garage should take into account the light trespass onto the runways and aprons as well as other facilities.

4.1.2 Sunlight Capture

Before the era of reliable artificial light sources, buildings were entirely naturally lit during daylight hours. Architectural design took into account all the ways light could come into a building, be it directly from the sun, diffused through the sky, or reflected off the ground and neighboring buildings (Figure 21).

The most effective designs also responded to differences in light quality coming from orientation. In the northern hemisphere, a southern exposure gets the most hours of direct sun, can use horizontal elements to control glare while preserving view, and receives varying amounts of light through the day. A northern exposure, by comparison, gets little direct sun, therefore seeing steady light through the day and requiring little control. Facades facing east and west get half a day of direct sun low on the horizon (Figure 22), often diminished by vertical elements that interfere with any view, and receive the most variable amount and quality of illumination in daylight hours.

Even partially illuminating a parking garage with natural light would create several advantages. The design could conserve energy if controls reduce artificial lighting when enough natural illumination is present. Daylight gives the best color rendering capability for viewing surfaces and people. The openings allowing daylight in provide views out. Well-designed natural lighting can enliven the interior for visitors, lessening a sense of claustrophobia that can come from spaces with low structure overhead and deep floor plates.

There would be disadvantages as well, primarily the potential for glare, either directly from the sun, or reflected off surfaces such as shiny metal or glass on vehicles. Contrast between the luminance of surfaces outside versus inside can interfere with visibility. The variability of direct and diffuse natural light with orientation, time, and weather makes control difficult. Drivers need their eyes to adapt to the difference in luminance when entering a parking garage during daylight hours.

For a discussion of glare in airport operations, see the Light Trespass section in Chapter 3.

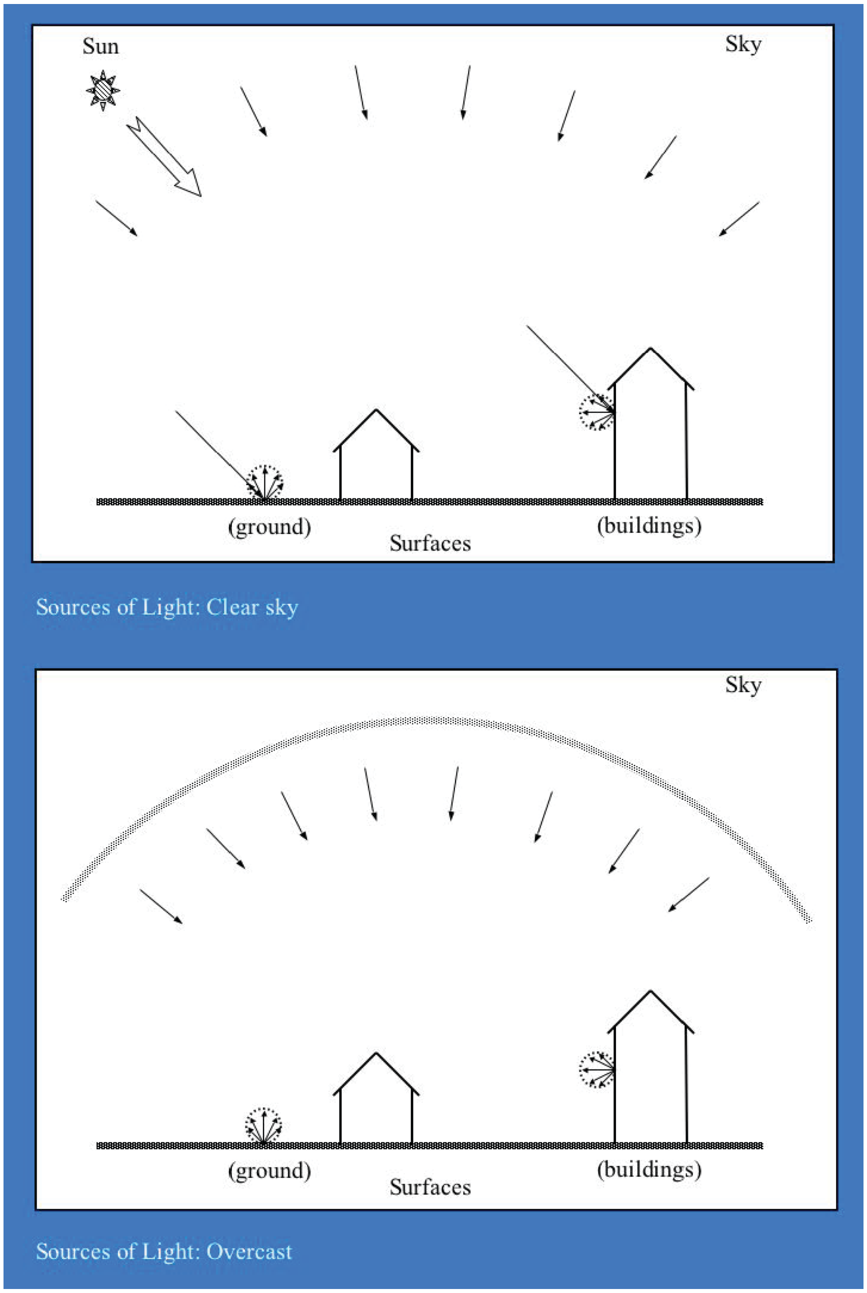

Figure 21. Sources of sunlight including direct from the sun. Source: Parsons Brinckerhoff analysis.

4.2 Architecture

4.2.1 Top Level

Most of the concerns relating to the top levels of the garage are covered in other sections such as Ramps and Light Trespass in Chapter 3.

4.2.2 Perimeter

Garage structures typically exhibit low floor-to-floor heights between deep floor plates with extensive openings at the perimeter for ventilation. These openings provide opportunities to

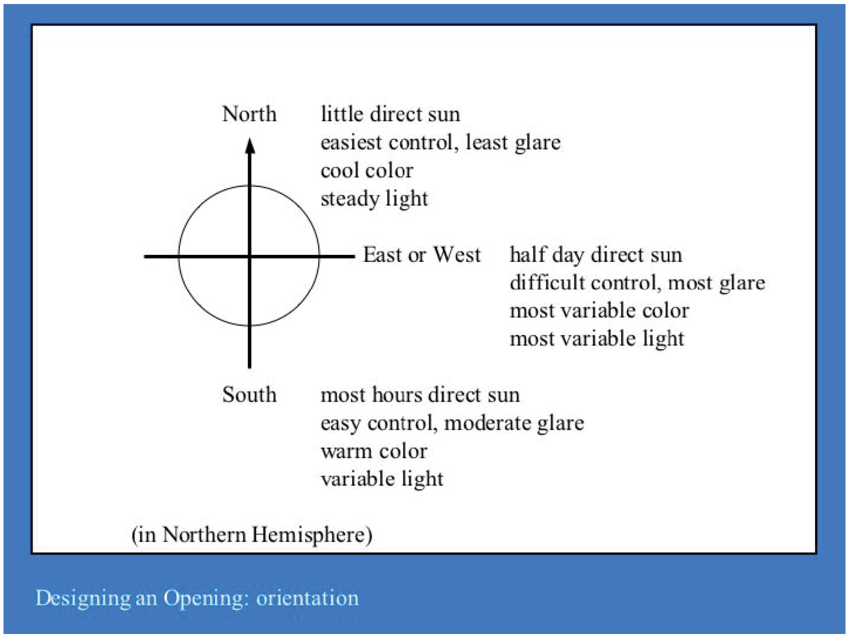

Figure 22. Effect of compass direction on the quality of daylight available. Source: Parsons Brinckerhoff analysis.

take advantage of natural light but usually allow it to enter indiscriminately. The ratio of short opening head height to long floor depth can make it difficult to daylight much of the interior effectively. From viewpoints deep within the garage, the scene beyond an opening can appear bright enough to interfere with visibility inside. Mitigating these effects and making use of natural illumination involves redistributing the daylight, making interior surface reflectances as high as practical, and controlling the luminance of the views out.

Redistributing daylight typically requires a reflector or refractor at the perimeter opening to capture natural light incident on that aperture and direct it up and in toward the interior. The bottom of the reflector or refractor must be above average standing eye level to prevent glare. A reflector can take the form of a light shelf, that is, a single horizontal object mounted in the opening, or a set of louvers (Figure 23). The top surface of the shelf or each louver can be specular or diffuse. A specular (Figure 24) light shelf would get the deepest penetration but needs the most precise design effort and installation coordination. An advantage of a shelf over a louver system is that the shelf can shade the lower part of the opening, thereby reducing contrast. Louvers and light shelves for daylighting can now be purchased as standard products. If the louvers are moveable, they can be adjusted to varying natural light conditions.

4.2.3 Pavement and Vertical Surface Reflectivity

Surface reflectances affect lighting design both quantitatively and qualitatively. The higher the average reflectance throughout a space, the less initial light is needed to produce a target illuminance. The higher the reflectance, the more uniform will be the light distribution. A space with all low reflectances and lighting directed mostly downward appears to have high contrast, producing reactions that vary from "dramatic" to "gloomy" or even "threatening." A room of all high reflectances will feel bright, prompting responses that could range from "cheerful" to "sterile." These effects might not be in proportion to the illuminance that could be measured.

Light-reflecting elements can mitigate the effect of a bright view to the outside by simply blocking part of the view while redirecting natural light. If the redirected light illuminates a

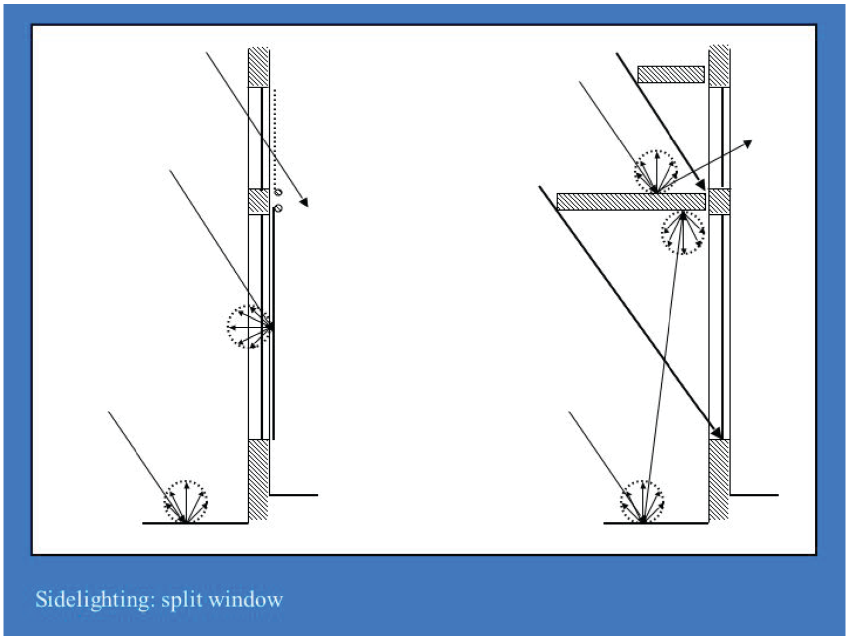

Figure 23. Utilizing reflective surfaces to increase the amount of daylighting. Source: Parsons Brinckerhoff analysis.

surface near the perimeter opening, then contrast between the inside and outside is reduced. Shaping the structure and infill so that surfaces are angled toward the opening can encourage this reduction in contrast (Figure 25). For the lower part of an exterior opening, decorative screening can reduce the brightness of the view out while allowing the necessary ventilation.

For daylighting, once the light is redirected from the perimeter, it is most useful if diffused. The best diffusion comes from high reflectance matte surfaces (Figure 24). That means flat white

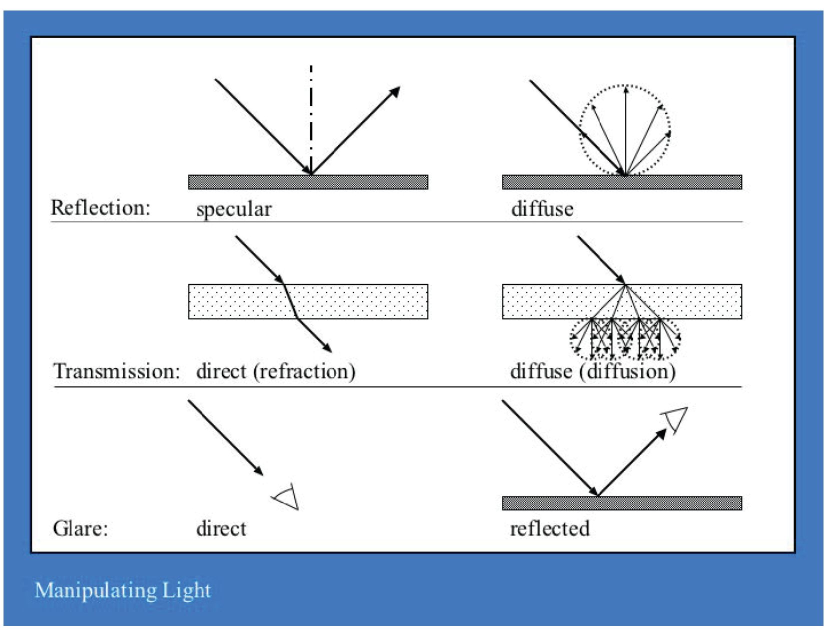

Figure 24. Specular versus diffuse reflection, direct versus diffuse transmission, direct versus reflected glare. Source: Parsons Brinckerhoff analysis.

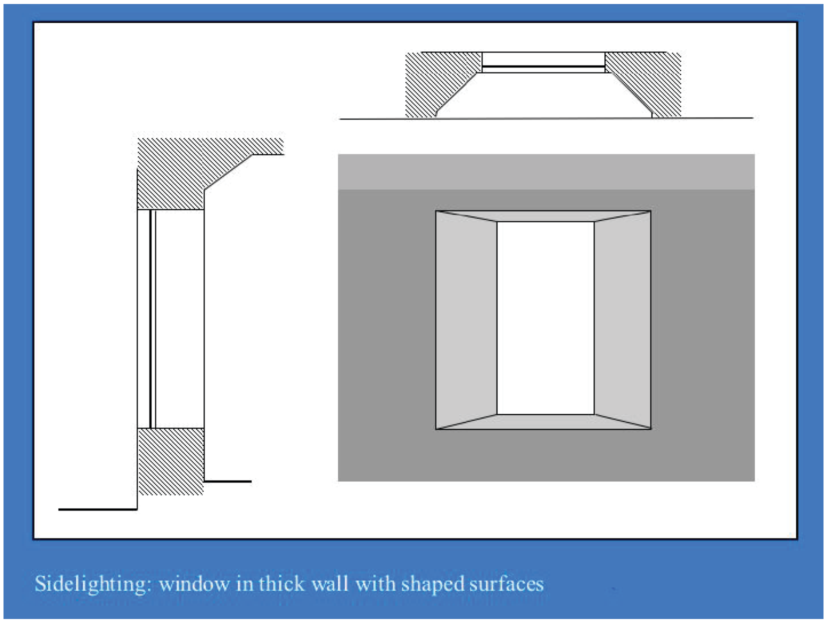

Figure 25. Shaping of openings to reduce contrast between indoors and out. Source: Parsons Brinckerhoff analysis.

paint on as much of the garage structure and infill as possible, especially the underside of floor slabs and the sides and bottoms of beams. If the columns and floors can be similarly coated, then so much the better.

Standard reflectances of surfaces in a garage tend to be those of bare concrete, which is usually in the range of 20% to 30% when new. Paint for concrete and masonry is readily available with reflectance of 80% or higher. These values will decrease over time with the accumulation of dirt but can be recovered if the surfaces are cleaned. The common combination of low surface reflectances, light directed almost entirely downward, and multiple shadows from vehicles can result in an environment that feels insecure to users, especially to those unfamiliar with it.

Allowances need to be made with regard to the reflectance of the pavement for both sunlight and luminaire performance. Since the goals of garage lighting are to illuminate the roadway, pedestrians, and so forth, the reflectance properties of the pavement will affect how well a driver or pedestrian can see the pavement as well as drive lane and parking spot markings. In general, concrete surfaces provide a more diffuse reflection than asphalt. In addition, the darker the pavement type, the more illuminance will be required to provide the lighting needed.

The lighting recommendations in this guide were developed with respect to a medium concrete surface. Adjustments up or down need to be made for other pavement types as provided in RP-8.

4.2.4 Stairwells/Elevators

Refer to RP-20 guidance. Current practice seems to follow RP-20 and no reason was found to provide differing guidance.

4.2.5 Ramps, Entrances, and Exits

Again, RP-20 guidance appears to be working well for transitioning from bright outdoors into the darker interior of airport parking garages. Be careful of not introducing glare with the relatively bright lighting of an entrance by using vertical cutoffs (luminaire or architectural) to limit the vertical illuminance directed toward the drivers.

4.2.6 Pedestrian Exits/Entrances

Current practice seems to follow IESNA RP-20 with no complaints from garage patrons.

4.2.7 Signage

Signage is very important to wayfinding for both pedestrians and patrons. The authors found that in some situations, due to the large size of the garage, some patrons had a difficult time determining which direction to head to find the terminal.

Utilizing lighting to highlight the existing signage will attract the attention of the patrons and enable improved wayfinding.

Glare to Airfield Operations

This is covered in the Light Trespass section of the Designing for Lighting Performance chapter.

4.3 Retrofit Issues

4.3.1 Available Electric Power

In most cases, technology transition will enable more efficient lighting to be installed lowering the electrical load in the garage overall. Airport authorities should consider this an opportunity to provide increased services or comforts for airport garage patrons in order to attract more customers. New services might include parking spots for electric vehicles with dedicated chargers for the various styles of connection. Increased lighting can be implemented in areas such as walkways to the terminals, as well as in the rental car and/or loading and unloading areas.

4.3.2 Available Electrical Circuits

Adding electrical circuits may be required for certain lighting control technologies. In some cases this may be cost-prohibitive. There are wireless and automated control technologies that install at each luminaire, enabling individually addressable control and or occupation/daytime control for energy savings as described in the next chapter.

CHAPTER 5

Lighting Operation Options

5.1 Current and Alternative Operation Practices

Luminaires with low power consumption can reduce operating costs. Also, the control methodologies available with the new light sources, LEDs in particular, create opportunities to implement lighting systems that are able to be dimmed and adapted to the needs of the users of the space. The Energy Technology Assistance Program (ETAP) investigates bi-level lighting retrofits in parking lots and garages for energy-use optimization based on the occupancy of the parking lot or garage. The program also provides technical assistance and cash rebates. Using energy-efficient luminaires and implementing adaptive lighting, energy usage can be reduced by 20% to 70% (ETAP, 2011).

5.2 Luminaire Selection

One way to save energy and minimize costs is to replace existing light fixtures with energy-efficient, high-performance fixtures, including LED, IFL, and FL.

5.3 Light-Triggered Adaptation

One approach to save energy is to control some of the luminaires with a dusk-to-dawn plug-in sensor. This is an established technology that works with all luminaires. These sensors, which are usually standardized, simply turn on the luminaire when the illuminance drops below a preset value, and turns off the luminaire when the illuminance exceeds a certain preset value. They require no connection to time-of-day or other control circuits. Based on current building design practices, there is usually significant lighting provided by sunlight in the first one or two bays from the outside of the garage, but this is highly dependent upon siting and design of the overhangs, knee walls, openings, and ceiling height, so a sunlight survey is required.

5.4 Usage-Driven Adaptation

5.4.1 Volume Peaks

When adopting usage-driven adaptive lighting, energy consumption is associated with the level of activity in the parking garage. Airport garages do not have the same pattern of user volume as other parking garages, because flights arrive and depart during a longer time span than typical business and retail hours. Although airports differ from each other in operating hours, most flights operate between 5 a.m. and 12 a.m., so in many airports, there is a low-volume window of four to five hours where lighting could be reduced. Also, while airport garages see significant vehicular occupation and traffic most hours of the day, in large, long-term parking garages, the usage of individual bays and drive lanes can be quite low.

Establishing a particular airport's hours of operation, flight schedule, and traffic patterns, and performing a cost-benefit analysis, would help determine if usage-driven adaptive lighting is the best approach for a particular airport garage's lighting design.

5.4.2 On/Off Adaptive Lighting

Luminaires can be turned on when vehicles and pedestrians are present, and off when they are not. Since there is a move to provide patrons with better information about the location of available spaces, there may be some synergy where the occupancy sensors can also trigger the lighting. Another low-complexity approach uses local motion-detection sensors and timers. When vehicles pass, and for a certain time after they pass, the luminaires would be turned on. At other times, they would be turned off.

On/off adaptive systems require luminaires that can be rapidly power cycled without significantly reducing the lamp life. Those include fluorescent and inductive fluorescent lamps, LEDs, and OLEDs.

5.4.3 Bi- and Multi-Level Adaptive Lighting

On/off is not the only adaptive lighting approach—for those luminaires that can be dimmed, bi- and multi-level adaptive lighting approaches are also possible. MH lamps can be dimmed, and LEDs and OLEDs can be both rapidly turned on and off and dimmed. OLEDs can be prohibitively expensive, LEDs less so, and both can be dimmed nearly infinitely. Most LED luminaires are designed for dimming, and are available with a dimmable drive circuit operated via a 1- to 10-volt controller. In addition, wireless technology can be harnessed to communicate with a controller at the luminaire. That way, the sensors controlling the luminaire need not be located at the luminaire itself, and the luminaire can be driven using a number of inputs, including occupancy sensing, volume adaptation, and light-level adaptation, all using a single control system.

Moreover, bi-level retrofits provide other advantages, such as reducing the maintenance cost and increasing the safety and security; controlling the lighting level, which can be used to alert drivers and pedestrians of approaching vehicles; increasing visual acuity with higher color temperatures; and better illuminating darker spots within the parking structure with uniform light distribution.

Table 11 shows bi-level parking lot and garage project financials (ETAP, 2011), in an example in which the following assumptions have been made:

- ETAP rebate levels: LED $200/fixture, T8/T5/Induction $100/fixture, lamp and ballast retrofit (garage only) $40/fixture
- number of fixtures: 175 for garages, 45 for lots—1-for-1 retrofits
- annual operating hours: 8,760 for garages, 4,380 for lots
- bi-level fixtures operate at 50% power 25% of the time
- energy rate: $0.15/kWh
- standard utility rebate: $0.05/kWh and $100/peak kW reduction
- estimated maintenance savings: $25 per fixture for garages, $100 per fixture for lots.

Recommendation: When considering adopting an energy-saving lighting design, consider luminaire selection, the potential for ETAP rebates, and light- and user-adaptive lighting.

Table 11. Bi-level parking lot and garage project financials.

Existing			Retrofit		Project Summary					
Location Type	Existing Fixture	Existing kWh	Fixture	Proposed kWh	kWh Saving x 1000	Annual Energy Cost Savings	Total ETAP Rebate	Utility Incentive	Net Project Cost	Payback in Years
Parking Garage	150W HPS	287,438	90W LED, bi-level	120,724	167	$25.0k	$35.0k	$10.0k	$93k	3.54
Parking Garage	100W HPS	211,554	New vapor lite	72,434	139	$21.9k	$17.5k	$8.5k	$47k	2.02
Parking Lot	100W MH	90,272	220W LED	37,942	52.3	$7.85k	$9.0k	$2.6k	$26k	2.76
Parking Lot	250W HPS	58,145	150W Induct	27,766	30.4	$4.55k	$4.5k	$1.5k	$19k	3.27

Source: VTTI compiled from ETAP data

CHAPTER 6

General Safety

Parking garages are considered critical security locations with a high potential for crime. There are a number of reasons for this: parking areas are usually public, they can be large and vacant, and they often have many corners, beams, parked vehicles, and other dark hiding places. Because parking garages have foot and vehicle traffic, it is easy for a loitering criminal to blend in with other pedestrians or drivers. Parking garages, in particular, have much less natural surveillance compared to parking lots because they are partially or fully enclosed (Jeremy, 1996).

A number of case studies have shown that providing proper lighting can reduce car break-ins, robberies, vandalism, and burglaries. Crime Prevention Through Environmental Design (CPTED) can be adopted to enhance the security of the parking garages. CPTED designs consider many parking garage features, like natural surveillance, stair towers, elevators, access control, signs and graphics, and restrooms. Among CPTED considerations, lighting is the most strongly recommended passive security feature. With respect to lighting, CPTED shares many themes with the RP-20 guidelines, but CPTED goes beyond the RP-20 to recommend the following (Jeremy, 1996):

- Illuminance: Both horizontal and vertical illuminance need to be carefully considered. While horizontal illuminance provides lighting on horizontal surfaces, which is useful for seeing the ground, the vertical illuminance provides lighting on vertical objects such as signs and keyholes and for facial recognition.
- Uniformity: The maximum or average illuminance divided by the minimum illuminance gives the uniformity ratio. The uniformity should be assessed not only for driving aisles but also for the edge of parking stalls to avoid transitions between light and dark areas.
- Glare: Glare is a general problem, but it is most critical to senior citizens and individuals with impaired vision. In glare conditions, it is difficult to clearly perceive objects because of the lack of contrast between the object and its background. Lights should be installed over parked vehicles rather than in the center of the aisle. In one-way routes, the lights can be installed near beams to provide shielding for glare reduction. Some light fixtures have built-in shields for the same purpose.
- Industry standards: The IESNA and the Parking Consultants Council (PCC) of the National Parking Association (NPA) provide some guidelines, as shown in Table 12.
- Level of service: Parking facility owners, city officials, and architects are familiar with the term level of service (LOS). In parking garage lighting design LOS is based on illuminance level and has different grades (e.g., grade A: superior design, B: above average, C: average, and D: below average but still passing) as shown in Table 13.
- Concrete stain: General brightness and uniformity can be enhanced by staining concrete, which is a cost-effective technique. It has the potential to even improve the lighting by one LOS. Paint can provide similar brightness, but maintenance cost is much higher. Staining of concrete may last more than 10 years.

Table 12. Industry standards for illumination for security.

Area	Horizontal Illumination (foot candles)	
	NPA	IESNA
Covered parking areas	-	5 (at night)
General parking areas	6	5
Minimum at bumper walls	2	1.25
Ramps and corners	-	10
Vehicle entrance	40	50
Vehicle exit	20	-
Stairwells, exit lobbies*	20	10 (low activity area) 15 (medium activity area) 20 (high activity area)
Roof and surface parking*	-	5 (vertical illuminance at 6 ft above pavement)
General parking areas	2	0.8 (low activity area) 2.4 (medium activity area) 3.6 (high activity area)
Vehicle ramps	-	0.5 (low activity area) 1.0 (medium activity area) 2.0 (high activity area)

*Average foot candles converted from minimums using 4:1 uniformity ratio
Source: VTTI compiled from Jeremy 1996 data

Table 13. Recommended horizontal and vertical illuminance levels for security.

		Maintained Illumination Levels per Level of Service (foot candles)			
		A	B	C	D
Average Horizontal Illuminance at Pavement	Covered parking areas	10	8-9	6-7	5
	Roof and surface parking areas	3	2.5	2	1
	Stairwells, elevator lobbies	20	16-18	12-14	10
	Uniformity ratio (avg:min)	3:1	3:1	4:1	4:1
	Uniformity ratio (max:min)	8:1	8:1	10:1	10:1
Minimum Vertical Illuminance at 42 in. Above Pavement	Covered parking areas	1.6	1.4	1.2	1
	Roof and surface parking areas	0.38	0.31	0.25	0.13
	Stairwells, elevator lobbies	2.5	2.1	1.6	1.3

Source: VTTI compiled from Jeremy 1996 data

CPTED can also reduce some costs associated with hiring security personnel. Even though including CPTED in the parking design process is relatively easy and inexpensive, most property owners and architects are not aware of its basic principles. As a result, some possibly more-expensive active security strategies, such as closed circuit television (CCTV) systems and security patrols, become necessary in poorly designed buildings (Jeremy, 1996).

Another study, essentially a literature review on lighting and security, examines nighttime lighting to find out whether it has an impact on crime or the fear of crime. No sufficient evidence was found to support a relationship between nighttime lighting and crime itself. However, a significant relationship was demonstrated to exist between the lighting and the fear of the crime (Heschong Mahone Group, 2008). There are mixed results on whether lighting can reduce crime, but it does affect the comfort of airport garage users.

Recommendation: When designing airport garage lighting, consider adopting CPTED recommendations.

CHAPTER 7

Cost-Benefit Considerations

The most widely used methodology for formal business case analysis is the benefit-cost analysis (BCA). This is an economic analysis comparing the benefits and the costs for the lifecycle of each initiative, and measures the overall economic value of the investment in terms meaningful to decision makers. The generally accepted industry practice is to use benefit-cost ratio (BCR) and net present value (NPV) as standard criteria for judging the lifecycle economic value of a program, although other metrics exist.

The BCA can be thought of as a decision support tool that helps program managers and decision makers choose among different courses of action and efficiently acquire and manage capital assets. The purpose of this analysis is to assess, in economic terms, whether the value received from a particular investment is outweighed by its costs. Under FAA guidelines, the value received, usually referred to as "benefits," considers the transportation system as a whole. It incorporates benefits accrued by passengers, airlines, airports, and the FAA. Costs include the total costs throughout the investment's lifecycle. These include initial acquisition costs, operations and maintenance (O&M) costs, and any required costs for mid-lifecycle technology upgrades, usually referred to as a "tech refresh." These concepts are described in more detail below, using guidance compiled in *ACRP Synthesis 13: Effective Practices for Preparing Airport Improvement Program Benefit-Cost Analysis* (Landau and Weisbrod, 2009):

- Benefit: The net value to society of all positive aspects of a construction project, acquisition, or other program, over the course of its lifecycle. Societal benefits cover all private, federal, and other public entities affected by the project. The term is usually used to focus on the economic value of such benefits, especially those that can be quantified. When benefits are expected to occur but cannot be measured in monetary terms, then they may be acknowledged in qualitative terms. However, qualitative benefit measures cannot be used in formal BCA as there are no monetary values to compare to costs.
- Cost: The net value to society of all expenses of a project over the course of its lifecycle. Costs include capital costs, O&M costs, tech refresh costs, and any termination costs. Capital costs refer to the investment, construction, and acquisition costs associated with the initial implementation of the project. O&M costs typically include labor, materials, supplies, and equipment costs. Tech refresh costs refer to costs incurred for mid-lifecycle technology upgrades. Termination costs cover dismantling and site restoration, as well as salvage value if the analysis time-frame ends before the useful life of the applicable facilities and equipment.
- Benefit-Cost Analysis: A business case analysis that evaluates the net economic value of an investment to society, by comparing the societal benefits associated with the project to its lifecycle costs. The term is usually used to mean a quantitative comparison of the economic value of benefits to costs, but can also include qualitative aspects. Because BCAs consider future economic value, they are inherently uncertain and therefore typically include a risk analysis. This risk adjustment expresses benefits and costs as probability distributions, and can be used

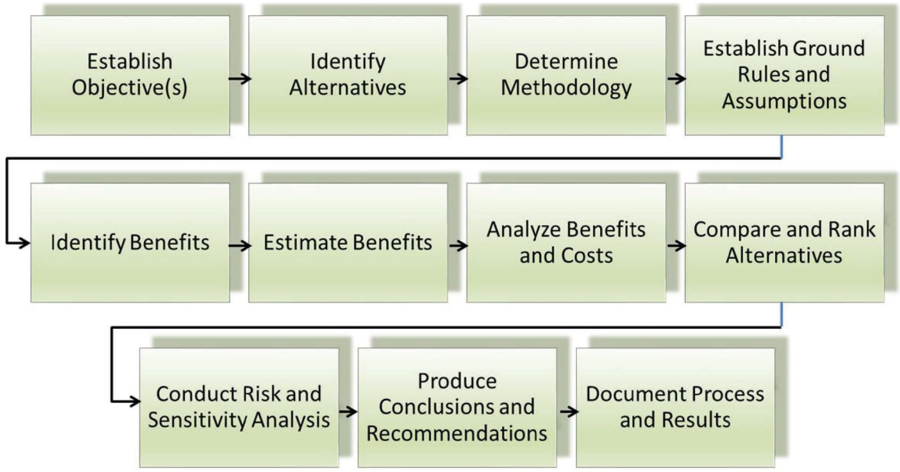

Figure 26. The BCA process. Source: MCR Federal.

to quantify the uncertainty, conduct sensitivity analysis, and incorporate varying degrees of pessimism or optimism.

Figure 26 illustrates the process that is traditionally used to develop business planning products for a broad range of airport and air traffic control investments. The process begins with identifying the objectives. This step helps identify other reasonable, feasible, and effective solutions that meet the objectives. The process then moves on to identifying, quantifying, and estimating costs and benefits, ranking and evaluating initiatives through benefit-cost ratios and other investment metrics, and performing sensitivity and risk analyses.

Airports are subject to a regulatory requirement to conduct a BCA for capacity-related projects funded through the federal Airport Improvement Program (AIP). Specifically, a BCA is required when $10 million or more in AIP discretionary funding is requested (FAA, 2011, p. 65769). As a result, lighting projects for airport parking structures are not subject to this requirement. However, FAA standards are still useful as a source for best practices. Even if a formal process is not required, conducting a BCA will help inform airports' investment decisions in regards to lighting projects. If the airport decides not to conduct a BCA, the principles described here will still be useful as general business planning guidance for lighting projects.

The sections below further describe key BCA concepts, including project lifecycle, benefits analysis, cost estimating, risk adjustment, and determination of the overall economic value. References are provided at the end of this document should the reader want to explore these concepts in more detail.

7.1 The Project Lifecycle

Selection of an appropriate project lifecycle enables costs and benefits of various alternatives to be evaluated objectively. Project requirements play a large part in determining the lifecycle. Normally the physical life of the asset would determine the lifecycle. For example, for a shuttle bus, runway, or airport terminal, suitable lifecycles might be 10, 20, and 30 years, respectively. For lighting projects, however, the physical life of lamps is most likely not the best choice of lifecycle duration for the economic analysis, since these are easily replaced. Selection of an evaluation period long enough to account for the increasing maintenance costs and periodic tech refreshes is important. Where a business case analysis is undertaken comparing different technologies with different longevities, a compromise intermediate lifecycle period is typically suggested. Lifecycle periods of between 10 and 20 years are most common for airport projects and are suitable for airport-lighting projects.

7.2 Assumptions

These assumptions are general in nature; more detailed assumptions are provided in the cost and benefit specific narratives below. The assumptions used here follow the guidelines provided by the FAA for business case planning for aviation infrastructure investments. They include:

- The present value of a benefit or cost stream is derived using the discount rate specified by the Office of Management and Budget (OMB), typically 7%.
- Benefits and costs are expressed in fiscal year (FY) constant dollars (i.e., real dollars).
- Conversion of constant dollars into then-year (TY) values is achieved using Gross Domestic Product (GDP) deflators or a Consumer Price Index (CPI) inflation adjustment factor:
  - Bureau of Economic Analysis, Table 1.1.9. Implicit Price Deflators for GDP: http://www.bea.gov/iTable/index_nipa.cfm
  - OMB, Budget of the United States Government Fiscal Year 2014, Table 2–1. Economic Assumptions: http://www.whitehouse.gov/sites/default/files/omb/budget/fy2014/assets/econ_analyses.pdf
- The present value of a benefit or cost stream is derived using the discount rate specified by the OMB:
  - OMB Circular No. A-94 Appendix C: http://www.whitehouse.gov/sites/default/files/omb/memoranda/2013/m-13-04.pdf

Once a lifecycle stream of the present value of benefits and costs has been obtained, the net present value can be calculated by simply taking the difference between the two.

7.3 Estimating Benefits

Benefits analysis is the process of identifying the physical or operational value of the goods or services that an initiative will yield over the analysis period. These are usually defined in physical or operational units (metrics) or terms that represent enhanced capability, which can then be quantified (FAA, 2013a). They can also be qualitative in nature, if quantification is not feasible. Typical benefits associated with airport parking garage lighting solutions might include utility cost savings, reduced CO_2 and greenhouse gas (GHG) emissions, and improved safety.

It is important to note that the FAA's approach to benefits analysis takes a system-wide approach. When considering benefits, the economic welfare of all air transportation service providers and users is considered. In other words, the total economic value of the benefits of an investment is the sum of the individual benefits accrued to the airport operators, passengers, airlines, other aircraft operators, and the FAA. In airport garage lighting applications, the most likely beneficiaries are the airport operators, passengers, and other parking garage users.

A general classification of benefit categories may include efficiency, environment, safety, and cost effectiveness. Note that this is a general classification that can be applied to any benefits analysis, but it does not necessarily follow that each initiative is predicted to achieve benefits in each of these four categories. Each of these categories is discussed further below.

7.3.1 Cost Effectiveness

This refers to benefits that reduce the airport sponsor's ownership costs or increase labor productivity. Cost-related benefits are measured either as potential cost savings or cost avoidance.

Benefits in productivity and efficiency can be measured using a variety of metrics, for example as labor costs monetized using compensation information for employees. For airport-parking-lighting applications, reductions in energy costs, maintenance-related labor costs, and lamp-replacement costs are likely benefit candidates.

7.3.2 Efficiency

This refers to benefits that improve the effectiveness of operations. Efficiency benefits are often measured as improvements to passengers' opportunity costs, monetized through the economic value of time spent traveling, or aircraft-operating costs. For airport garage lighting applications, efficiencies that benefit the users (i.e., passengers and aircraft operators) are likely to be secondary to cost savings for the airport operator, at least in terms of quantifiable benefits.

7.3.3 Environment

This refers to benefits that affect the environment. Typical environmental benefits associated with aviation infrastructure projects include decreased noise impact, improved air quality, and reduced GHG emissions. While there is no FAA-adopted methodology for monetizing GHG-emission reduction for a business case analysis, CO_2 reduction is often used as a quantitative proxy for total GHG reduction. EUROCONTROL provides several alternatives for monetizing GHG emissions in its standards for BCA calculations (EUROCONTROL, 2013). For airport garage lighting applications, reduction in air pollutants and GHG emissions are likely environmental benefits.

7.3.4 Safety

This refers to benefits that lower the risk of fatalities and injuries. Safety benefits are typically measured as a potential reduction in the number or severity of accidents. Safety-related benefits can be monetized using the economic cost of fatalities and injuries, using International Civil Aviation Organization injury classifications or other actuarial data. However, this method is only possible if a reduction in injuries or fatalities can be modeled as a function of the proposed improvements in airport garage lighting. In other cases, safety has to be treated as a qualitative benefit.

7.3.5 Quantitative Benefits

In a quantitative benefit analysis, the identified benefits are evaluated using metrics that can be converted into monetary values for each year in the lifecycle. The benefits estimates are then fed into the overall economic analysis to compare benefits against costs. Some observed practices for quantifying benefits are presented in *ACRP Synthesis 13: Effective Practices for Preparing Airport Improvement Program Benefit-Cost Analysis* (Landau and Weisbrod, 2009). Additionally, standard economic values used by the FAA to monetize benefits from the categories above are published annually by the Office of Investment Planning and Analysis (FAA, 2013b).

7.3.6 Qualitative Benefits

In some cases, it may be impossible or impractical to produce quantified, monetary values for expected benefits. Benefits that are expected to occur but cannot be measured in monetary terms should still be acknowledged and described in qualitative terms. Although qualitative benefit descriptions do not affect BCA calculations, they are still useful for conveying the advantages of the initiative to stakeholders. They can help decision makers to choose among alternatives whose quantified benefits have similar orders of magnitude.

Qualitative benefits will not have a numeric measure, so they should include a detailed description conveying the extent and scale of the improvements. The description should also illustrate the importance of these improvements to the stakeholders. In some cases a middle ground is possible, where benefits can be quantified, but not monetized (i.e., assigned a dollar value). Examples include reductions in GHG emissions, since there is no FAA-accepted standard for monetizing the value of CO_2 or other GHG emissions.

7.3.7 Benefits in Airport Parking Garage Lighting Applications

Cost effectiveness: Operations and maintenance cost savings. Next-generation lighting systems will likely provide reduced O&M costs as compared with the existing lighting system. This will stem from several factors, the drivers of which include:

- Electricity savings. Use of more efficient bulbs and dimming technology may generate significant cost savings.
- Maintenance costs (material and labor). Next-generation lighting systems are expected to utilize bulbs with a service life that has a longer mean time between failures. This will reduce the quantity of bulbs that need replacing and the labor required to do so.
- Vehicle costs (maintenance and fuel). Next-generation lighting solutions may have fewer associated repair and maintenance activities. The use of vehicles (trucks, forklifts, scissor lifts, etc.) may be reduced, generating cost savings over the lifecycle.

To quantify and monetize cost savings, it is expected that the following metrics will need to be captured.

- Project lifecycle (operational years).
- Power consumption (dimmed and full output).
- Quantity of lamps.
- Operating hours (times dimmed versus full output).
- Electricity rates at various times of day/week/month: current and predicted.
- Preventive/scheduled maintenance activities (frequency, costs for parts and materials, labor costs).
- Corrective/unscheduled maintenance activities (frequency, costs for parts and materials, labor costs).
- Cleaning (if not part of preventive maintenance).
- Vehicle use needed for installation, preventive maintenance, corrective maintenance, cleaning, fuel, vehicle maintenance, and procurement and lease costs should be considered.
- Lost revenue from closed spaces due to maintenance.
- Labor hours and rates (for actions described throughout the Work Breakdown Structure (WBS)).

Table 14. GHG calculation examples—aircraft fuel savings.

GHG	Conversion Factor (lbs per lbs of jet fuel)
CO_2	3.149
H_2O	1.230
SO_2	0.000840

Source: Data from FAA 2013b, compiled by MCR Federal

Environmental: GHG reductions. Since a major benefit of investing in new lighting technology in an airport garage is reduced energy consumption, the associated GHG reductions warrant special treatment. In FAA analyses of the economic value of investments in air traffic technologies, an analogous situation often exists where the investment is projected to result in fuel savings. This can be the result, for example, of reduced taxi times or optimized airborne trajectories. Fuel savings are monetized in a straightforward manner by the application of predicted fuel costs, which are provided by the FAA for this purpose (FAA, 2013b). Converting fuel savings to a reduction in GHG emissions is also relatively simple, since the relationship is established by the fuel-combustion process. Table 14 lists conversion factors for jet fuel savings to GHG emissions.

A similar approach can be used for converting savings in electrical consumption to reductions in GHG emissions. The U.S. Environmental Protection Agency (EPA) provides a GHG equivalence calculator that can be used for this purpose. The EPA's calculator uses the Emissions and Generation Resource Integrated Database to convert reductions of kilowatt-hours into reductions of CO_2 emissions. The EPA estimates a national average equivalence of 1 kWh $= 6.8927 \times 10^{-4}$ metric tons of CO_2, using 2010 values (EPA, 2014). For more detailed analyses, regional conversion factors are also available.

When comparing alternatives, quantifying the reduction in GHG emissions may be sufficient. Monetizing such reductions produces a richer analysis, however, as it allows for the consideration of tradeoffs between GHG emissions and other benefits and cost savings. The FAA guidelines for aviation-related BCAs do not include an accepted methodology for monetizing GHG emissions. However, since airport operators are only bound by FAA guidelines for large capacity-related airfield projects, other methodologies can be considered. One potential source is EUROCONTROL's guidance for the conduct of BCAs (EUROCONTROL, 2013). GHG monetization approaches focus on the value of CO_2 emissions. Methods exist for converting other GHGs to CO_2 equivalents in order to obtain a more complete assessment. The computed CO_2 equivalents are then monetized using the same price that is that used for CO_2. EUROCONTROL's recommended practice is based on future prices for the trading of CO_2 allowances in the European Emissions Allowance system, which are shown in Table 15.

Table 15. CO_2 pricing per metric ton.

Year	Low	Base	High
2014	$3.85	$6.11	$9.30

Source: Data from EUROCONTROL, 2013, compiled by MCR Federal

This method could be adopted in the United States by using a U.S. market for trading carbon allowances. One option is the Regional Greenhouse Gas Initiative (RGGI) operated by a group of Northeast and Mid-Atlantic states. In the most recent auction conducted under RGGI, the median price for a one-metric ton CO_2 allowance was $4.35 (Potomac Economics, 2014, p. 8).

7.3.8 Other Benefits

While this discussion of benefits covers the key benefits likely to result from investments in new lighting technologies for airport parking garages, other benefits should also be considered. These benefits, which generally will be described as qualitative benefits, are described in more detail in the following.

Safety. As discussed in the previous chapter, operational safety improvements are likely due to improved vertical illuminance, which improves pedestrian facial recognition and vehicle detection. However, quantifying this effect is difficult, unless a statistical model can be created that links lighting parameters to reductions in safety. Note that lighting-related safety is also influenced by factors that are not directly linked to the lighting technology under consideration, or where the link is partial. Examples include the provision of wayfinding features and the elimination of glare.

Security. The link between improved lighting and security, particularly reductions in property crime, has been established in numerous case studies and encoded in CPTED standards. CPTED guidance covers illuminance, uniformity, glare, and other lighting design parameters that affect security. As security improvements can be difficult to model and quantify, it is likely that security-related benefits should be treated as qualitative benefits. However, if security improvements can be linked to reductions in security-related labor costs or associated equipment, then the related benefits can be monetized as airport cost savings.

Comfort. Comfort refers to the users' perception of the lighting environment and is related to color, uniformity and both horizontal and vertical illuminance. For example, at the same illuminance level, white light is perceived to be more comfortable than yellowish light (Knight, 2010). While the existing level of comfort can be quantified using user surveys, these are often not practical for assessing proposed alternatives. Moreover, there is no accepted methodology for monetizing customer comfort. For these reasons, benefits associated with comfort are most likely to be treated as qualitative benefits. Note that there may be interdependencies between comfort-related benefits and other benefits, notably safety and security. Whenever interdependencies exist, care must be taken to avoid double counting the associated benefits.

7.4 Estimating Costs

7.4.1 Work Breakdown Structure

A WBS is a mechanism for identifying the set of activities needed to complete an investment decision, from initial planning to decommissioning. The establishment of a formal WBS ensures benefits and costs are identified in a systematic and comprehensive manner. While the WBS is generally established as part of the cost estimating process, it provides a structure for comparing benefits against costs throughout the entire acquisition lifecycle.

To establish a WBS for lighting-related projects for airport parking structures, the FAA's Acquisition Management System (AMS) WBS version 5.0 was used. The cost elements in Table 16 from FAA AMS WBS 5.0 were identified as relevant for evaluating the principal cost and benefit drivers.

Each element in the proposed WBS is described in more detail in the following.

WBS Element 1.1—Research, Engineering, and Development. Activities associated with exploring new opportunities for service delivery, solving problems with current operations,

Table 16. Sample work breakdown structure.

Phase 1: Mission Analysis
1.1 Research, Engineering, and Development
Phase 2: Investment Analysis
2.1 Investment Analysis
Phase 3: Solution Implementation
3.1 Hardware
3.2 Integration
3.3 Training
3.4 Program Management
3.5 Systems Engineering
3.6 Test and Evaluation
3.7 Technical Data
3.8 Implementation Planning, Management, and Control
3.9 Implementation Engineering
3.10 Site Preparation, Installation, Test, and Activation
Phase 4: In-Service Management
4.1 Maintenance
4.2 Program Planning, Authorization, Management, and Control
4.3 Integrated Logistics Support
4.4 Technical Data
4.5 Hardware Modification and Support
4.6 Utilities
4.7 Decommissioning

Source: MCR Federal analysis

defining and stabilizing requirements, maturing operational concepts, and mitigating risk. These activities generate information to quantify and characterize capability shortfalls, service needs and requirements, benefit expectations, and design alternatives.

WBS Element 2.1—Investment Analysis. Activities associated with analyzing alternative solutions in preparation for an investment decision; all activities associated with detailed planning for the alternative selected for implementation; solicitation of offers from potential suppliers; and development of required program documentation.

WBS Element 3.1—Hardware. All physical products and equipment procured to accomplish the goals of the investment program. It is expected that hardware will primarily consist of commercial off-the-shelf products, though customization may be necessary, in the following categories:

- Lamps,
- Fixtures,
- Controls,
- Ballasts/drivers,
- Wiring, and
- Transformers.

While trucks, forklifts, scissor lifts, and/or tools may also be necessary for implementation and maintenance, it is anticipated these assets might also have been needed for the existing lighting infrastructure and therefore may not be an extra expense beyond the status quo.

WBS Element 3.2—Integration. Activities associated with technical and engineering services during installation and integration of the technical solution into a larger host system or operational environment.

WBS Element 3.3—Training. Activities associated with planning, developing, and establishing training for operators and maintainers.

WBS Element 3.4—Program Management. Activities associated with business and administrative planning, organizing, directing, coordinating, controlling, and approval actions to accomplish overall program objectives.

WBS Element 3.5—Systems Engineering. Activities associated with planning, directing, and controlling a totally integrated engineering effort for a solution. Specific activities include requirements, definition, and allocation; analysis, design, and integration; supportability, maintainability, and reliability engineering; quality assurance; interface management; human factors engineering; security engineering; safety engineering; technical risk management; and specialty engineering.

WBS Element 3.6—Test and Evaluation. Activities associated with testing during product development to determine whether engineering design and development activities are complete; whether the product will meet specifications, security certification, and authorization criteria; and whether it is operating properly so as to achieve acceptance.

WBS Element 3.7—Technical Data. Activities associated with planning and reviewing program and contractor technical data. Technical data includes items such as engineering drawings, notebooks, maintenance handbooks, operator manuals, maintenance manuals, installation drawings, and all contract data deliverables.

WBS Element 3.8—Implementation Planning, Management, and Control. Activities associated with implementation planning, control, contract management, and business management. Specific activities include planning, organizing, directing, coordinating, estimating, scheduling, controlling, and approving actions to accomplish program implementation.

WBS Element 3.9—Implementation Engineering. Engineering activities associated with site surveys, design, analysis, and studies. Specific activities may include civil, electrical, mechanical, architectural, industrial, and other engineering services associated with developing plans and specifications for installation of the technical solution.

WBS Element 3.10—Site Preparation, Installation, Test, and Activation. Activities associated with site preparation, installation, acceptance testing, operations testing, and checkout of hardware, software, and equipment to achieve operational status. Specific activities include:

- Preparation and installation: Activities associated with site preparation, equipment installation, acceptance testing, and checkout of hardware and software to achieve operational status.
- Test and evaluation: Activities to verify and validate operational readiness following installation of the technical solution.
- Acceptance inspection and commissioning: Activities associated with preparing for and achieving declaration of operational readiness and full operational capability.
- Decommissioning and removal of replaced assets: All activities associated with the termination and removal of a decommissioned system or equipment.

WBS Element 4.1—Maintenance. Activities associated with preventive and corrective maintenance of hardware needed to maintain or restore fielded assets to an operational condition. Specific activities include:

- Failure identification
- Failure localization and isolation
- Disassembly, removal, and replacement or repair in-place
- Reassembly, checkout, and condition verification
- Packaging and shipping components to repair facilities.

WBS Element 4.2—Program Planning, Authorization, Management, and Control. Activities associated with planning, authorizing, and managing actions that must be accomplished for operation and maintenance.

WBS Element 4.3—Integrated Logistics Support. Activities associated with executing, monitoring, evaluating, and adjusting integrated logistics support for systems, facilities, and equipment over their operational life.

WBS Element 4.4—Technical Data. Documentation activities, including engineering drawings, operator manuals, maintenance manuals, repair and test procedures, logistics management information, and other technical data associated with the operations and maintenance of operational systems, facilities, and equipment.

WBS Element 4.5—Hardware Modification and Support. Activities associated with the analysis, design, test, and implementation of modifications during the fielded technical solution's lifecycle to include tech refresh.

WBS Element 4.6—Utilities. Recurring utility costs including water, electric, gas, oil, etc.

WBS Element 4.7—Decommissioning. Activities associated with disposition of decommissioned systems and equipment at the end of the fielded technical solution's lifecycle.

7.4.2 Costs

Costs are determined by populating the WBS above. This approach sequentially organizes work by functional category. It is important to time phase costs by year, and to capture the lowest level of detail available.

Non-recurring costs. The non-recurring capital-investment costs will be the total expenses incurred in Phases 1 through 3 of the WBS presented above, which includes mission analysis, investment analysis, and solution implementation. The technical solution drives the cost analysis, and its development is the focus of the mission and investment analyses. The capital costs will vary considerably depending on the size of the parking structure and the condition of the existing lighting system (if not a greenfield installation) and the extent to which it can be retrofitted for the next-generation lighting solution. There may be parts of the existing system that can be reused in the next-generation system.

The physical equipment (WBS Element 3.1) needed for the next-generation lighting system is expected to consist of lamps, fixtures, controls, ballasts/drivers, wiring, and transformers. Determining what may be reused or retrofitted to an existing system may result in costs savings as compared to a greenfield installation.

The implementation of the technical solution will span numerous cost elements found in Phase 3. Site preparation, installation, integration, and testing are key steps in the process along with engineering and program management. These activities may involve costs from one or more contracted vendors as well as from program-office staff working for the airport operator.

Recurring costs. The recurring costs will stem from the operations- and maintenance-related costs of Phase 4, In-Service Management. There are expected to be several recurring cost drivers. Maintenance will include the preventative and corrective actions needed to maintain the next-generation lighting system throughout its deployed lifecycle. Maintenance costs include the cost of the materials as well as the labor and equipment needed to perform the repair or replacement.

Electricity costs of the next-generation lighting systems are expected to be lower through the use of more efficient bulbs and dimming technologies, but may constitute the largest overall cost. Decommissioning may be assumed to be outside the scope of the analysis, if it is assumed the lighting system will still be functioning and necessary at the end of the lifecycle. Program management of operations may not vary significantly from the status quo.

7.5 Lifecycle Economic Value

To assess the economic value of a potential investment, benefit and cost streams need to be standardized across the same lifecycle durations and discounted at prevailing rates to determine their respective present values. Benefits can then be compared against costs using evaluation criteria such as NPV, BCR, return on investment (ROI), internal rate of return (IRR), and payback period. These methodologies for assessing the lifecycle economic value are described in more detail below.

7.5.1 Quantitative Versus Qualitative Evaluation

In determining the economic value of an investment using the BCA methodology, the focus is on quantitative measures, especially those that can be monetized. Advantages of quantified measures include ease of comparison, the ability to analyze the impact of changes, and explanatory power. The latter can be particularly useful when investment alternatives are reviewed by stakeholders or decision makers. The use of quantified benefits can minimize some of the risks associated with the subjective evaluation of investments, such as the introduction of biases.

When investments can be quantified but not monetized, special care must be taken in the use of the resulting benefit computations. In particular, it must be clearly established that the quantified metric represents a system benefit. The links between the investment, the operational improvements that follow, and the quantified measure must be clearly defined. Presuming that the benefit in question has been properly vetted and defined, the associated metric can be useful in supporting the investment decision, particularly in cases where the monetized economic values of two competing alternatives are close.

Qualitative benefits that cannot be expressed numerically can be used to augment the quantitative analysis by providing additional background information or highlighting a specific benefit mechanism. They can help stakeholders and decision makers understand differences between alternatives that have similar quantitative benefits. When qualitative aspects are included in the benefits case, the related descriptions should clearly describe the importance of the benefit under discussion. In other words, the mechanism by which the qualitative benefits provide value to the airport or its users must be well defined.

7.5.2 Discounting

Most airport investments involve the expenditure of large blocks of resources (represented by costs) at the outset of the project in return for a future flow of benefits. Although these benefits and costs are in the form of dollars, year-to-year benefits and costs cannot simply be summed into totals and then compared. Rather, the analyst must take into account the fact that dollars paid out or earned in the near term are worth more in "present value" than are dollars paid out or earned in the far-term. This procedure establishes whether or not benefits exceed costs for any or all of the alternatives. The alternative that has the greatest net present value is considered the preferred choice. The process of converting future cash flows into present value is called discounting.

The opportunity cost of money accounts for the need to discount dollar amounts to account for the passage of time. The opportunity cost of capital reflects the fact that, even without inflation, the present value of a dollar to be received a year in the future is less than the value of a dollar in-hand today. A dollar in-hand can be invested immediately and provide a return for a period of one year. A dollar to be received one year from now cannot provide a return for the investor during this period.

Discounting requires the application of an annual discount rate to future benefits and costs. The annual discount rate (also known as the marginal rate of return of capital) represents the prevailing level of capital productivity that can be achieved at any particular time by investing resources, i.e., the opportunity cost. Because the FAA recommends the use of constant dollar cash streams, the discount rate should be net of inflation. This net-of-inflation rate is called the real discount rate. The real discount rate relevant to all airport projects to be funded with federal grant funds is set by the FAA at 7% (FAA, 2013b). This value, in turn, is established by guidance provided by the Office of Management and Budget (OMB, 1992). Note that for airport parking garage lighting applications, airports may not be required to use the FAA-specified discount rate. In that case, the airport should follow its internal guidance or use its own best estimate of the opportunity cost of money.

Note that the process of discounting tends to put more weight on costs than on benefits. This is because costs tend to accrue earlier in the lifecycle of an investment, and discounting increases as time increases.

7.5.3 Legacy Case

The legacy case represents the current lighting system and operating conditions, as well as near-term changes in assets, systems, facilities, people and processes that have already been funded. It does not include any additional investment (e.g., technology refreshment of system components) beyond what is already included in a program's most recent budget approval. The legacy case service period typically differs from proposed alternatives, as its remaining economic service life is frequently less than the lifecycle of the proposed improvements. Economic analysis in support of investment decisions requires the lifecycle period of the legacy case to match that of the alternatives under considerations. This frequently necessitates the modeling of a legacy case refresh of hardware and software of similar capability (i.e., with no improved functionality), in order to match the lifecycles of the alternatives under evaluation.

7.5.4 Metrics

The present value of incremental costs and benefits can be compared in a variety of ways to determine which, if any, option is most worth pursuing. In some cases, no alternative will generate a net benefit relative to the base case—a finding that would argue for pursuit of the no-build or base-case scenario. The following are the most widely used present-value comparison methods: NPV, ROI, BCR, IRR, and payback period. These metrics are the key instruments used to measure the net economic value of an investment. In general, they are only applied to benefits and costs that can be monetized.

Net present value is defined as the difference between the present value of cash inflows (benefits) and the present value of cash outflows (costs). The present value of benefits or costs is calculated as:

$$PV = \frac{FV}{(1+i)^n}$$

where:

PV is present value
FV is future value
i is discount rate
n is period

The factor used to discount future value is a function of the discount rate and the year in the lifecycle. Since a discount rate of 7% is standard for aviation investments, the resulting factors are independent of the investment under consideration. Computations for a 10-year lifecycle beginning FY 2014 are shown in Table 17.

The NPV method requires that in order to warrant investment of funds, an alternative must have a positive NPV, and have the highest NPV of all tested alternatives. The first condition ensures that the alternative is worth undertaking relative to the base case, i.e., it contributes more in incremental benefits than it absorbs in incremental costs. The second condition ensures that maximum benefits (in a situation of unrestricted access to capital funds) are obtained. NPV is the most widely used and theoretically accurate economic method for selecting among investment alternatives. However, NPV does have certain conceptual and analytical

Table 17. Factors for calculating present value.

Fiscal Year:	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023
PV Factor:	1.0000	0.9346	0.8734	0.8163	0.7629	0.7130	0.6663	0.6227	0.5820	0.5439

Source: MCR Federal analysis

limitations, which makes consideration of other present-value-evaluation methods appropriate in some instances.

Return on investment. ROI provides a relative measure of the NPV. It can be used to compare different alternatives (although care must be taken to make sure the assumptions are consistent across the comparison). It is defined as the NPV divided by the present value of the lifecycle costs (i.e., discounted costs).

Benefit-cost ratio. The BCR is defined as the present value of benefits divided by the present value of costs. A proposed activity with a ratio of discounted benefits to costs of one or more will return at least as much in benefits as it costs to undertake, indicating that the activity is worth undertaking. The principal advantage of the benefit-cost ratio is that it is intuitively understood by most people. Moreover, this method does provide a correct answer as to which objectives should be undertaken—defined as those with ratios greater than or equal to one. It is also less effective for comparing mutually exclusive projects of different scale or different levels of capital intensity and operating expense. Finally, scoping issues regarding the inclusion of common costs and benefits can cause variability in the derived BCR that the NPV methodology avoids.

The BCR is computed as the present value of benefits divided by the present value of costs. The ratio measures efficiency of spending. The decision criterion is usually to accept only projects with a BCR greater than one, which indicates a positive NPV. An advantage of BCR is that it ignores project size, and therefore does not result in bias towards larger projects. This method is suitable for alternatives with unequal costs and unequal benefits. For monetized benefits, the BCR allows for analogies. For example, if the BCR = 2, the analogy is that for every $1 spent, there are $2 in benefits.

Internal rate of return. IRR is defined as that discount rate which equates the present value of the stream of expected benefits in excess of expected costs to zero. In other words, it is the highest discount rate at which the project will not have a negative NPV. To apply the IRR criterion, it is necessary to compute the IRR and then compare it with the FAA-prescribed 7% discount rate or another discount rate used. A project with a higher IRR should generally be accepted over one with a lower IRR. If the real IRR is less than 7%, the project may not be worth undertaking relative to the base case.

Payback period. The payback period measures the number of years required for the net benefits to recover the initial investment in a project. In other words, it measures the time required to recover a project's original investment with discounted cash flows. Alternatives with shorter payback periods are generally preferred over those with longer periods. One characteristic of this evaluation method is that it favors projects with near-term benefits. However, the payback period method fails to consider benefits beyond the payback period. Also, it does not provide any information on whether an investment is worth undertaking in the first place.

7.5.5 Risk Adjustment

BCA risk adjustment is an objective evaluation of the proposed investment to quantify the impact of uncertainty in the lifecycle of the investment. The estimation of benefits and costs is forward-looking, and therefore predictive in nature. Risk analysis provides methods for incorporating the probabilistic nature of such predictions. Identification and quantification of cost, benefit, and schedule risks enable the development of risk-adjusted estimates. Accounting for risk increases the likelihood that the delivered product will meet stated performance goals. Generally, three methods are used (Landau and Weisbrod, 2009):

- Sensitivity analysis, where variations in the results are observed by changing one or several input variables at a time. Variables that are highly sensitive should be the focus of the subsequent risk adjustment and stakeholder reviews.
- Probabilistic methods, where distributions are applied to some or all input variables and sampling techniques are used to determine distributions surrounding the resulting metrics.
- Scenario-based methods, where "low," "medium," and "high" scenarios incorporate varying degrees of pessimism or optimism about growth in demand or savings associated with future projects.

A benefit of using probabilistic methods is that they allow the benefits and costs to be stated as confidence intervals. This type of analysis is performed by identifying key drivers of uncertainties in the benefits and costs. These variables are then assigned appropriate risk ranges, expressed as probability distributions. Variables that are associated with higher levels of uncertainty and variability are assigned greater risk ranges. Software tools such as Crystal Ball can then be used to calculate confidence intervals using a Monte Carlo simulation that runs a large number of iterations of benefit and cost estimates, using the probabilistic benefit and cost drivers as inputs. To ensure that the resulting BCA is conservative, it is standard practice to use the 20th percentile of the resulting benefit distribution and the 80th percentile of the cost distribution.

CHAPTER 8

Other Considerations

8.1 Environmental Stewardship

There is significant pressure from modern society to be better stewards of the environment, biosphere, and planet. Environmental stewardship takes many forms, but the most relevant to airport garage lighting include:

- Efficient usage of limited resources and more reliance on renewable sources. This is a primary driver to transitioning technologies, especially when considering an end-of-life replacement of luminaires. Significant resources are provided by power companies, as well as local and federal government agencies to encourage transition to more efficient technologies. These resources include DOE grants, power company rebates, low-interest loans, escrows, etc., all of which can contribute to easing the initial capital investment.
- Reduction of the production of greenhouse gases and other pollution.
- Reduced waste production/increased recycling of waste.

8.2 Provision of New Customer Service in the Garage

Another consideration for investing in more efficient technology is the overall capacity of the installed electrical circuits in the parking garages. The power needs of airport patrons are constantly increasing. Adding amenities such as electric car charging stations for patrons and for rental commerce may require significant investment in electrical infrastructure in the garage unless circuits can be freed up by lighting that utilizes less power to produce the same light levels. The freed-up electrical power may enable more highlight lighting.

8.3 Customer Comfort

Customer comfort is essential to attracting new customers as well as keeping existing customers. Airports require customers as any business does. Therefore, providing ease of wayfinding, decreased fear of crime, and increased visibility all add to customer comfort in using the garage. In addition, customer comfort due to space conditioning may become more possible when energy is freed up from transitioning to more efficient lighting.

8.4 Other Financial Considerations

The number of luminaires needed for replacement in an airport garage can be quite significant, and can present significant bargaining power for buyers. In addition, manufacturers of the newer lighting technologies are eager to gain adoption and thus increase sales of these products which represent significant investments. Therefore, it is possible for airports to use their purchasing power to acquire a demonstration of a variety of lighting technologies in situ at little cost to the airport operation authority. Purchasing power can also be used to negotiate the overall cost of the investment to directly affect the ROI. This is particularly true for medium- and large-sized airports.

CHAPTER 9

Case Studies

9.1 Parking Garage Lighting Comparison

A sample lighting design has been prepared that will allow for a direct comparison of the light sources. This design was prepared to meet the requirements of RP-20.

A typical parking structure has double loaded bi-directional travel aisles, creating a situation where pedestrians must pass both between the parked cars and across travel lanes. The surfaces of a garage tend to have low reflectance, the maintenance is difficult at times, and ceiling heights tend to be low, requiring luminaires that provide both horizontal and vertical illuminance while minimizing excessive direct glare.

A 60-ft by 50-ft area made up of two structural bays with a floor-to-ceiling height of 14 ft 3 in. and a structural depth of 2 ft 6 in. is illustrated in Figure 27. There are many options for the construction of a garage. In this case, a precast structural TT slab—a floor slab with two reinforcing vertical webs that in cross-section resembles two T's placed side by side—would allow luminaires to be raised into the structure, limiting direct glare.

To accurately model the parking garage lighting from the various light sources, an LLF is to be established that takes into account the differences in the sources' operating characteristics, luminaire efficiency, and maintenance cycles for cleaning the facility. The LLFs used in this comparison are shown in Table 18.

A comparison layout of four luminaires placed over the travel line at the edges of the parking stripes was used to generate a series of relative comparisons of calculated lighting. The lighting on the surfaces in the calculation represents horizontal illumination on the floor plane and vertical illumination in each direction at 5 ft above the finished floor. The OLED and LEP sources were omitted from the calculation comparison because neither source has a practical luminaire for garage lighting. The results are shown in Table 19.

The comparison reveals the benefits of the alternatives. The LED system had the highest relative efficiency compared to the fluorescent. Similarly, the LED had the best uniformity. It did, however, have the lowest average horizontal illuminance. The other technologies provided higher average illuminance levels with a higher power consumption.

9.2 Bi-Level Lighting Savings Example

California State University, Sacramento (CSUS), and the University of California, Santa Barbara (UCSB), conducted two case studies for bi-level lighting systems. CSUS and UCSB conducted the case studies in partnership with the California Lighting Technology Center (CLTC), UC Davis, and the California Energy Commission's Public Interest Energy Research (PIER). Neither case study evaluated people's responses to or feelings about the parking garage lighting.

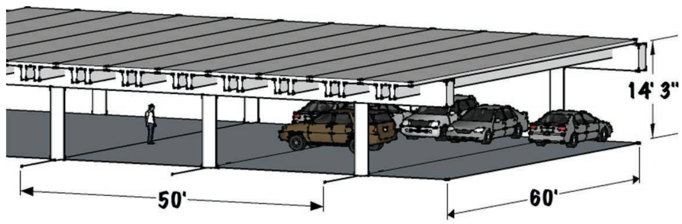

Figure 27. Parking lot structure for design comparison. Source: Created by Parsons Brinckerhoff.

Table 18. Light loss factors for compared light sources.

SOURCE COMPARISON – LIGHT LOSS FACTORS (LLF)							
Source	FL	IFL	HPS	CMH	LED	OLED	LEP
LLF	.63	.67	.62	.66	.68	.63	.70

Source: Compiled by Parsons Brinckerhoff

Table 19. Light source comparison in sample garage calculations.

SOURCE COMPARISON – Calculated Values for Identical Layouts						
SOURCE		FL	IFL	HPS	CMH	LED
Horizontal Illuminance (fc)	MAX	4.8	5.7	5.8	6.3	3.8
	MIN	1.1	1.7	2.6	2.6	1.7
	MAX/MIN	4.36	3.35	2.23	2.42	2.24
Vertical Illuminance EAST-(fc)	MAX	3.8	5.2	6.5	7.6	4.4
	MIN	0.6	0.9	1.5	1.1	0.8
	MAX/MIN	6.33	5.78	4.33	6.91	5.5
Vertical Illuminance NORTH-(fc)	MAX	4.8	5.4	7.1	6.7	4.4
	MIN	1.1	1.9	2.9	3.2	2.3
	MAX/MIN	4.36	2.84	2.45	2.09	1.91
Vertical Illuminance SOUTH-(fc)	MAX	4.7	5.4	7.1	6.8	4.4
	MIN	1.1	1.9	3.2	3.5	2.1
	MAX/MIN	4.27	2.84	2.22	1.94	2.10
Vertical Illuminance WEST-(fc)	MAX	3.8	5.2	6.5	7.6	4.4
	MIN	0.6	0.9	1.5	1.1	0.8
	MAX/MIN	6.33	5.78	4.33	6.91	5.50
Total Load - W (4 Luminaires)		240 W	347 W	412 W	444 W	196 W
Relative Efficiency FL = 100%	MIN(fc)/W	100%	106%	137%	128%	189%

Source: Parsons Brinckerhoff analysis

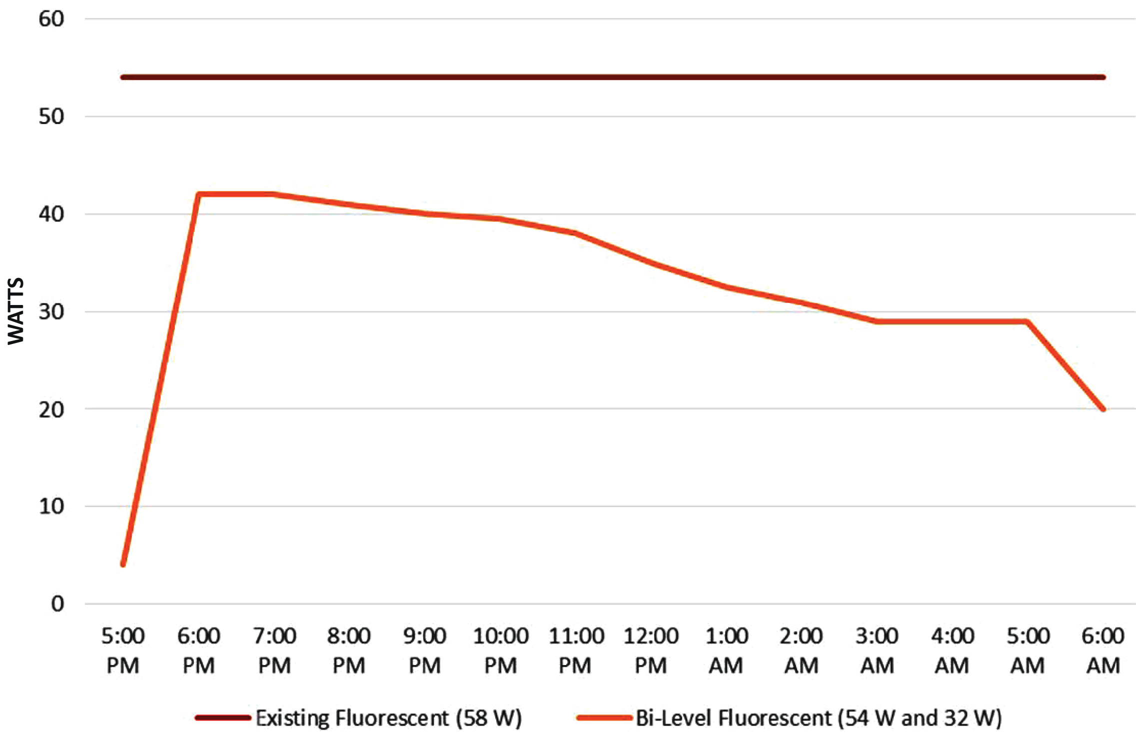

Figure 28. Approximate energy-consumption levels for fluorescent and bi-level fluorescent lighting systems. Source: Created by VTTI from PIER 2009 data.

In the case of UCSB, 30 existing fluorescent fixtures in a parking garage were retrofitted. The resulting energy consumption and savings can be seen in Figure 28 and Table 20 (PIER, 2009).

In the case of CSUS, 30 high pressure sodium luminaires were retrofitted with LED luminaires. The resulting energy consumption and savings can be seen in Figure 29 and Table 21 (PIER, 2008).

9.3 Effects of Various Surface Reflectances

A model of a portion of a typical garage similar to the one at Boston's Logan Airport Terminal B was adjusted and calculated with surface reflectances varied for comparison on the ceiling, walls, beams and columns. This was modeled using AGI32 software which allows calculation of

Table 20. Savings from using bi-level dimmable fluorescent lamps versus standard fluorescent lamps.

	System size (Watts)	Lifecycle energy cost (energy at $0.128/kWh) (20 yr life)	Lifecycle maintenance cost (labor at $100/hr) (lamp cost $2.65)	Total lifecycle cost
Standard Fluorescent	58	$33,174	$7,898	$41,071
Bi-Level Dimmable Fluorescent	54	$25,638	$7,898	$33,533
Savings		$7,538		$7,538

Source: VTTI compiled from PIER 2009 data

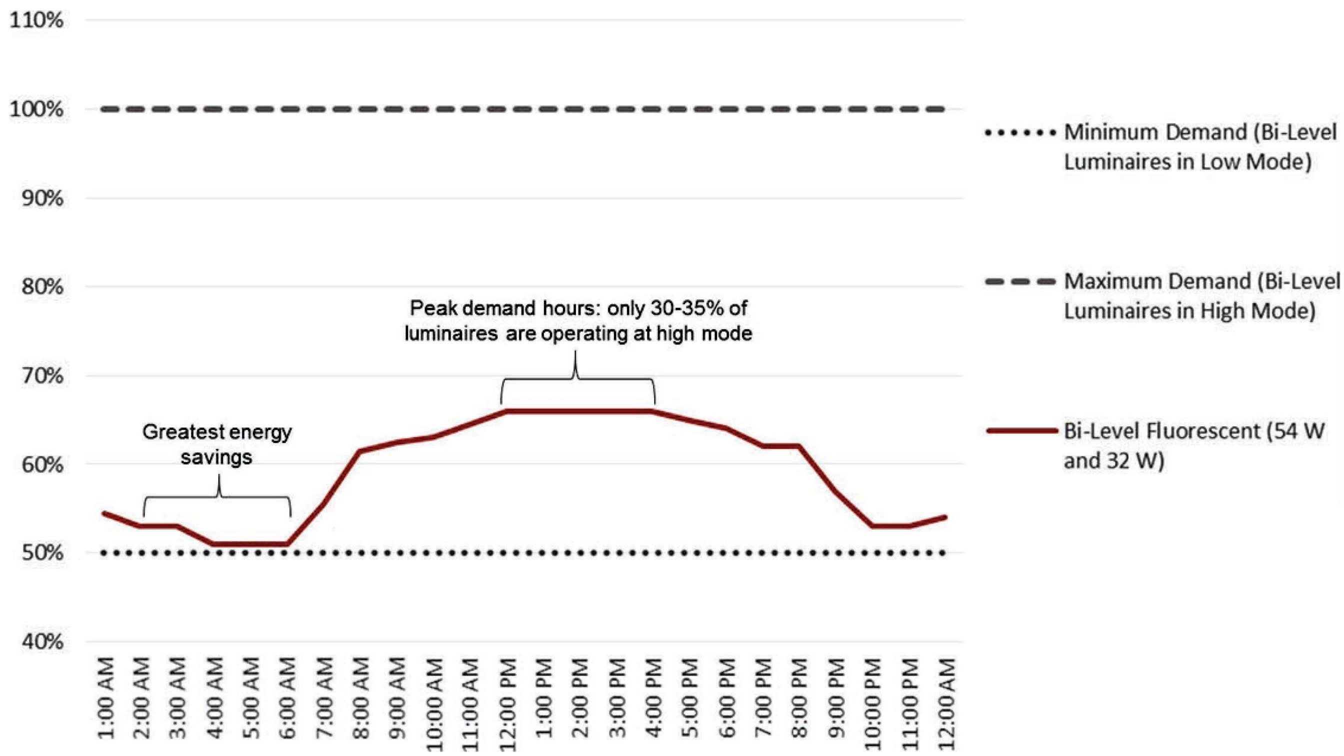

Figure 29. Bi-level energy consumption (PIER, 2008). Source: VTTI compiled from PIER 2009 data.

the effects of reflectance, luminaire distribution, and shadowing. The calculation results can be seen in Table 22, Table 23, Figure 30, and Figure 31. FC is the illuminance in foot candles, and AFF stands for "above the finished floor."

Comparing the measurement results to calculations performed for Boston Logan's B terminal garage (Table 22), the measured illuminances were quite a bit higher than those predicted. Virginia Tech Transportation Institute measured 111 lx average horizontal and 104 lx average vertical illuminances. This is higher than the calculations of 59 lx and 40 lx for low reflectivity. This could be due to higher reflectances from the vehicles occupying the space, especially since RP-20 and the model assume no vehicles in the garage. It could also be due to a difference in spacing between the luminaires in the model and the as installed luminaires or running the luminaires at a higher current level. Figure 32 illustrates a real-world application of low reflection illumination. As can be seen, the ceiling is shadowed and darker than the floor, similar to the illustration in Figure 30. Also, similar to the model, the vehicles and pedestrians are in positive contrast to the background.

Table 21. Savings from using LED lamps versus HPS lamps.

	System size (Watts)	Lifecycle energy cost (energy at $0.128/kWh) (20 yr life)	Lifecycle maintenance cost (labor at $100/hr) (lamp cost $100)	Total lifecycle cost
HPS	189	$2,419	$210	$2,629
LED	165	$1,661	$150	$1,811
Savings		$758	$60	$818

Source: VTTI compiled from PIER 2008 data

Table 22. Boston Logan Terminal B model calculations with low reflectance.

Calculation with reflectances of 10%	Average	Minimum	Max:Min
Horizontal illuminance, 0’ AFF	5.50FC (59lx)	2.9FC (31lx)	2.52
Vertical illuminance at low hor. illum., 5’ AFF	3.76FC (40lx)	0.9FC (9.7lx)	8.78

Source: Parsons Brinckerhoff analysis

Table 23. Boston Logan Terminal B model calculations with high reflectance.

Calculation with reflectances of 80%	Average	Minimum	Max:Min
Horizontal illuminance, 0’ AFF	6.27FC (67lx)	4.2FC (45lx)	1.88
Vertical illuminance at low hor. illum., 5’ AFF	4.38FC (47lx)	1.9FC (20lx)	4.42

Source: Parsons Brinckerhoff analysis

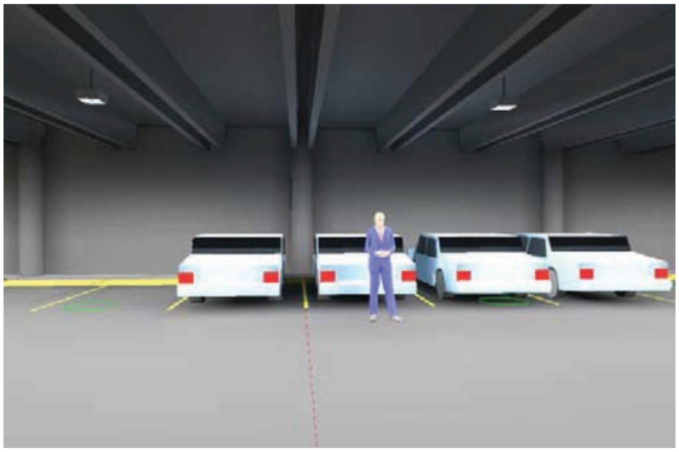

Figure 30. Surface reflectances at 10%.
Source: Parsons Brinckerhoff analysis.

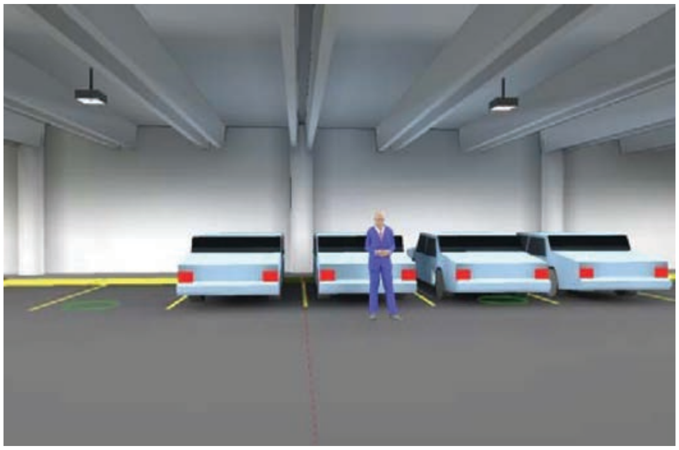

Figure 31. Surface reflectances at 80%.
Source: Parsons Brinckerhoff analysis.

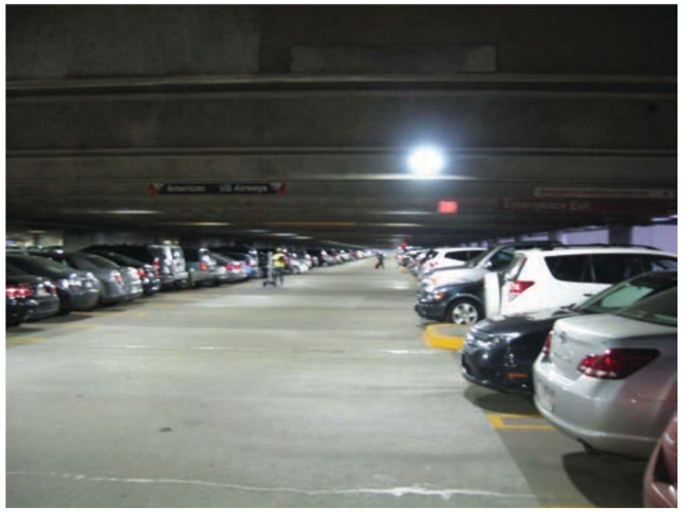

Figure 32. Boston Terminal B illustrating low reflectance lighting in application. Source: VTTI.

9.4 Sample Benefit-Cost Calculation

A simplified benefit calculation is shown in Table 24 to highlight some of the concepts discussed above. This example considers only two quantified benefits: cost savings due to decreased demand for electricity and the associated reduction in CO_2 emissions. The example uses a 15-year lifecycle starting in FY 2014. A 7% discount rate is used to compute the present value of the lifecycle benefits. The energy savings for the entire lighting installation has been estimated at 92,843 kWh per year. This amount is assumed to remain constant throughout the lifecycle.

Table 24. Sample benefits calculation.

Year	Energy Savings (kWh)	CO_2 Reduction (metric tons)	Utility Rate (FY14 $/kWh)	Energy Savings (FY14 $)	CO_2 Reduction (FY14 $)	Total Benefit (FY14 $)	Present Value (FY14 $)
2014	92,843	64	$0.1000	$9,284	$278	$9,563	$9,563
2015	92,843	64	$0.1012	$9,395	$278	$9,674	$9,041
2016	92,843	64	$0.1025	$9,519	$278	$9,797	$8,557
2017	92,843	64	$0.1036	$9,623	$278	$9,901	$8,082
2018	92,843	64	$0.1049	$9,739	$278	$10,018	$7,642
2019	92,843	64	$0.1061	$9,852	$278	$10,131	$7,223
2020	92,843	64	$0.1074	$9,970	$278	$10,248	$6,829
2021	92,843	64	$0.1086	$10,087	$278	$10,366	$6,455
2022	92,843	64	$0.1099	$10,206	$278	$10,485	$6,102
2023	92,843	64	$0.1112	$10,326	$278	$10,605	$5,768
2024	92,843	64	$0.1125	$10,448	$278	$10,727	$5,453
2025	92,843	64	$0.1139	$10,571	$278	$10,850	$5,155
2026	92,843	64	$0.1152	$10,696	$278	$10,974	$4,873
2027	92,843	64	$0.1166	$10,822	$278	$11,100	$4,606
2028	92,843	64	$0.1179	$10,950	$278	$11,228	$4,354
Total:	1,392,644	960		$151,489	$4,176	$155,665	$99,704

Source: MCR Federal analysis

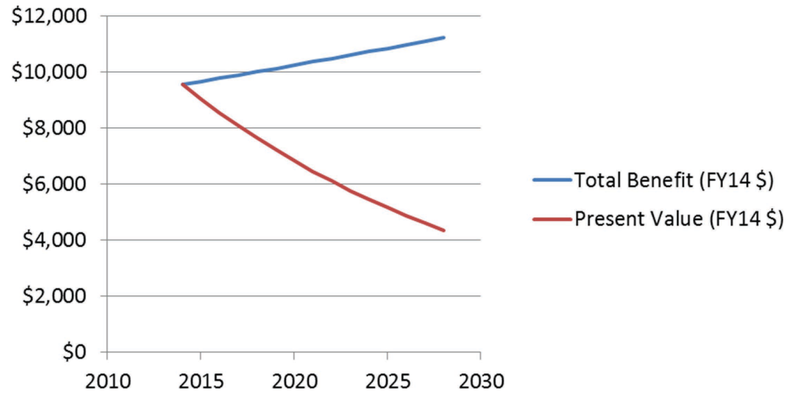

Figure 33. Total benefits before and after discounting (7% discount rate). Source: MCR Federal analysis.

In this example, the decrease in energy consumption is converted to a reduction in CO_2 using the average EPA value of 6.8927×10^{-4} metric tons of CO_2 per kWh of electricity generation (EPA, 2014). CO_2 reductions are monetized at $4.35 per metric ton of CO_2 (Potomac Economics, 2014, p. 8). The price of CO_2 is assumed to remain constant throughout the lifecycle.

The example assumes an electricity cost of $0.10/kWh, with an annual escalation of 3%. However, since the BCA methodology requires the benefit streams to be expressed in real dollars, the resulting utility rate has been normalized using GDP deflators. This corrects the cost of electricity for inflation. The resulting utility rate is shown in constant (i.e., real) FY 2014 dollars.

In this case, the monetized benefit is the sum of the electrical cost savings, computed by applying the utility rate to the energy saved per year, and the monetized value of the associated reductions in CO_2 emissions. These yearly sums are then converted to a present value benefit stream using the FAA standard 7% discount rate. The conversion from real to present value dollars accounts for the opportunity cost of money. Since the discounting is compounded throughout the lifecycle, the impact of the conversion to present value dollars is substantial. This is especially true for benefits near the end of the lifecycle. Figure 33 plots the total benefits before and after discounting, to illustrate the impact of this conversion.

While this highly simplified example omits many of the benefits that would be expected in a next-generation lighting installation, such as maintenance and replacement cost savings, it illustrates the key principles of monetizing benefits. As discussed, the example also demonstrates the impact of using the present value of the monetized benefits. Also notable is the relatively minor monetary contribution of CO_2 reductions relative to the economic value of the associated savings in energy costs.

Not shown in this example is the risk adjustment that would normally be conducted in order to account for uncertainty in key benefit drivers. A number of other factors have the potential to substantially affect the results. In a real-world application, ranges of low, best, and high values would be established for these drivers, for a probabilistic analysis of risks. Key drivers from this example that are candidates for risk adjustment include:

- Annual energy savings,
- Utility cost and/or escalation rate, and
- Monetization of CO_2 reduction and its escalation rate (assumed to be zero in the example).

CHAPTER 10

Conclusions and Final Remarks

Significant opportunities have developed in the last 20 years for efficient airport parking garage lighting. No longer are designers limited to high pressure sodium as the lighting technology of choice. Airports provide a unique combination of issues for parking garage lighting. Security, wayfinding, and usability are all components of the application of light to airport spaces. With pressure to reduce costs and environmental impacts, these issues have become much more pressing. There is no technology approach that was clearly hands-down better than the others at the time this guide was written. However, each technology offers different strengths, which provide more options for providing garage lighting solutions. Benefits that the customers can enjoy are improved lighting while they are in the garage, better color recognition, and an increased sense of security and safety with improved light uniformity and distribution. The freed-up electric power will enable airports to offer improved amenities such as electric car charging stations. In addition to encouraging electric car use, more efficient lighting technologies enable airport authorities to reduce their environmental impact by using less energy, as well as producing less pollutants and less waste. Finally, there exists real cost savings from reduced power usage and maintenance.

APPENDIX A

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APPENDIX B

Glossary of Terms

The terms used in this section are included here with some description regarding how they apply to the specific sources discussed in this report.

Correlated color temperature (CCT) – The absolute temperature of a blackbody whose chromaticity most nearly resembles that of a light source. This is seen when heating a piece of metal: first it becomes slightly red, then bright red, then orange, and then bright white. Sources with a lower CCT appear more yellow, red, and orange (often defined as warmer), and sources with higher CCT appear more white, shifting to green and blue (often defined as cooler).

Color rendering index (CRI) – Measure of the degree of color shift objects undergo when illuminated by the light source as compared with the color of those same objects when illuminated by a reference source of comparable color temperature.

Illuminance – The areal density of luminous flux incident on a surface, measured in lux (lx).

Horizontal illuminance – The illuminance falling on a horizontal plane.

Lumen – The SI unit of luminous flux. Radiometrically, it is determined from the radiant power. Photometrically, it is the luminous flux emitted within a unit solid angle (one steradian) by a point source having a uniform luminous intensity of one candela.

Lumen maintenance – The lumen maintenance of a source is shown as the percentage of reduction in lumen output of the source over time. Most sources will degrade in output depending on hours of operation.

Luminaire efficiency – The ratio of the luminous flux emitted by the luminaire to that emitted by the lamp or lamps used therein. For this report, the term will refer to luminaire lumens divided by total lamp lumens.

Luminance – The luminous flux leaving a surface in a given direction, measured in candelas per meter squared (cd/m^2).

Luminous efficacy – The quotient of the total luminous flux emitted by the total lamp power input, expressed in terms of lumens/watt. For this report, it is used as the total lumens produced by the lamp divided by the total power consumed by the light sources and ballast/driver.

Mesopic – Light levels between the photopic and scotopic levels, typical of roadway lighting.

Photopic – High light-level conditions, where visual field luminances are over approximately 3.4 cd/m^2.

Rated life – The life value assigned to a particular type of lamp. Different sources are rated in different ways. Some have rated life stated as a certain percentage of lamp failures, and others are rated by a certain percentage of lumen depreciation of the source.

RoHS/TCLP – Reduction of Hazardous Substances, which is a European directive restricting lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyl (PBB), and polybrominated diphenyl ether (PBDE) in electronics products; and Toxic Characteristic Leaching Procedure, which is a procedure to classify waste as hazardous or non-hazardous under the U.S. Resource Conservation & Recovery Act.

Scotopic – Low light-level conditions, where the visual field luminances are less than 0.001 cd/m^2, well below moonlight levels.

Vertical illuminance – The illuminance falling on a vertical plane.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation