



Illuminating
ENGINEERING SOCIETY

IES RES-2-19

IES Research Report: Lighting for Parking Facilities

**IES Research Report:
Lighting for Parking Facilities**

Final Report prepared for the Illuminating Engineering Society

June 2018

Rajaram Bhagavathula, Ronald Gibbons, and Alejandra Medina-Flintsch

Center for Infrastructure-Based Safety Systems

Virginia Tech Transportation Institute



Copyright 2019 by the Illuminating Engineering Society.

All rights reserved. No part of this publication may be reproduced in any form, in any electronic retrieval system or otherwise, without prior written permission of the IES.

Published by the Illuminating Engineering Society, 120 Wall Street, New York, New York 10005.

Printed in the United States of America.

ISBN# 978-0-87995-000-2

DISCLAIMER

IES publications are developed through the consensus standards development process approved by the American National Standards Institute. This process brings together volunteers representing varied viewpoints and interests to achieve consensus on lighting recommendations. While the IES administers the process and establishes policies and procedures to promote fairness in the development of consensus, it makes no guaranty or warranty as to the accuracy or completeness of any information published herein.

The IES disclaims liability for any injury to persons or property or other damages of any nature whatsoever, whether special, indirect, consequential or compensatory, directly or indirectly resulting from the publication, use of, or reliance on this document.

In issuing and making this document available, the IES is not undertaking to render professional or other services for or on behalf of any person or entity. Nor is the IES undertaking to perform any duty owed by any person or entity to someone else. Anyone using this document should rely on his or her own independent judgment or, as appropriate, seek the advice of a competent professional in determining the exercise of reasonable care in any given circumstances.

The IES has no power, nor does it undertake, to police or enforce compliance with the contents of this document. Nor does the IES list, certify, test or inspect products, designs, or installations for compliance with this document. Any certification or statement of compliance with the requirements of this document shall not be attributable to the IES and is solely the responsibility of the certifier or maker of the statement.

Acknowledgements

Southern California Edison's Engineering Services group is responsible for implementing this project. This report was developed as part of Southern California Edison's Emerging Technologies and Codes & Standards Programs under internal project number ET17SCE1220. The Project Team conducted this lighting technology evaluation with overall guidance and management from the project collaborative team listed below. This project was co-funded by the Illuminating Engineering Society (IES).

Energy Solutions (Project Management)

Christopher Uraine
curaine@energy-solution.com
(510) 482-4420 x243

Michael McGaraghan
mmcgaraghan@energy-solution.com
(510) 482-4420 x242

Southern California Edison (Co-funder)

Randall Higa
Randall.Higa@sce.com
(606) 454-5545

David Rivers
david.g.rivers@sce.com
(626) 302-0827

Illuminating Engineering Society (Co-funder)

Brian Liebel, Director of Standards and Research
bliebel@ies.org
(917) 855-1065

Kevin Houser, Editor-in-Chief, Leukos
kwh101@psu.edu

Virginia Tech Transportation Institute (Principal Investigator)

Rajaram Bhagavathula
RBhagavathula@vtti.vt.edu
(540) 231-5209

Ronald Gibbons
rgibbons@vtti.vt.edu
(540) 231-1581

Alejandra Medina-Flintsch

CONTENTS

Executive Summary	I
List Of Figures	III
List Of Tables	V
1.0 Introduction	1
1.1 Gaps In Research	3
2.0 Critical Task Analysis	4
2.1 Insurance Claim Investigation	4
2.2 National Electronic Injury Surveillance System (NEISS)	4
2.3 Not-In-Traffic Surveillance (NITS)	5
2.3.1 Maneuver Type	5
2.3.2 Crash Type	5
2.3.3 Pedestrian Crashes	6
2.3.4 Motor Vehicle Crashes	6
3.0 Background: Naturalistic Driving Study Data From Strategic Highway Research Program 2	7
3.1 Pre-Incident Maneuver	8
3.2 Precipitating Event	9
3.3 Event Nature	10
3.4 Incident Type	10
3.5 Driver Behavior	11
3.6 Summary Of Injuries, Crashes, And Incidents In Parking Lots And Parking Garages	12
3.7 Critical Tasks For Parking Lots And Garages	13
3.7.1 Visual Tasks For Drivers	14
3.7.2 Visual Tasks For Pedestrians	14
3.7.3 List Of Critical Visual Tasks For Evaluation Of Lighting In Parking Facilities	15
4.0 Assessment Objectives	16
5.0 Methods	17
5.1 Experimental Design	17
5.2 Detection Tasks	17
5.2.1 Wheel Stop Detection	17
5.2.2 Facial And Hand Recognition	18
5.2.3 Detection Of Side-Facing Pedestrian	18
5.2.4 Pedestrian Detection At Stopping Sight Distance	18
5.2.5 Detection Of Reversing Vehicles	18
5.3 Independent Variables	19
5.3.1 Light Source Type	19

5.4	Light Level	19
5.4.1	Age.....	20
5.5	Dependent Variables	20
5.5.1	Detection.....	20
5.5.2	Perception Of Visibility, Comfort, And Safety	20
5.6	Participants	21
5.7	Procedure	22
5.7.1	Screening.....	22
5.7.2	Pedestrian Task	22
5.7.3	Driver Task.....	23
5.7.4	Wrap Up	24
5.8	Analysis	24
5.8.1	Visual Performance Analysis.....	24
5.8.2	Subjective Ratings Analyses	25
6.0	Results	26
6.1	Parking Garage	26
6.1.1	Visual Performance	26
6.1.2	Subjective Ratings	26
6.2	Parking Lot	28
6.2.1	Asphalt Pavement – Visual Performance	28
6.2.2	Asphalt Pavement – Subjective Ratings	29
6.2.3	Concrete Pavement – Visual Performance.....	31
6.2.4	Concrete Pavement – Subjective Ratings.....	31
7.0	Discussion	33
7.1	Effects Of Light Level	33
7.2	Effect Of Light Source.....	33
7.3	Effects Of Age	34
7.4	Practical Implications	34
7.5	Limitations.....	35
8.0	Conclusions	36
9.0	Recommendations	37
10.0	References	38
11.0	Abbreviations And Acronyms	40
12.0	Appendix: Project Timeline	41

Executive Summary

PROJECT GOAL – The goal of this study was to understand the effects of lighting source types and light levels on the visual performance of pedestrians and drivers on the critical visual tasks in parking lots and garages. The results of this study will inform the lighting level recommendations for parking facilities in IES Recommended Practice (RP) documents.

TECHNOLOGY DESCRIPTION – In the current study, pedestrians’ and drivers’ visual performance and their perceptions of safety, comfort, and visibility were evaluated at a parking garage and at parking lots with asphalt and concrete pavements under three light source types (high pressure sodium luminaires, 3000-K light-emitting diode [LED] luminaires, and 5000-K LED luminaires) and at multiple light levels. Visual performance involved facial and hand recognition, wheel stop detection, detection of a side-facing pedestrian, and detection of a vehicle backing up from a parking spot. Perceptions of safety, comfort, and visibility were assessed by means of a questionnaire.

PROJECT FINDINGS – Results showed that in the parking garage, an increase in light level beyond 10 lux of average horizontal pavement illuminance did not result in a statistically significant increase in visual performance or perceptions of safety, comfort, and visibility. For parking lots of asphalt and concrete pavements, this plateauing was observed at the 2-lux light level. No statistical differences were observed between the light source types for the visual performance tasks, but the perceptions of safety, comfort, and visibility were highest for the 5000-K LED luminaires.

PROJECT RECOMMENDATIONS – The recommended light levels for parking lots should be revised to an average pavement illuminance of 2 lux, and those in the parking garage should be set at an average pavement illuminance of 10 lux, to ensure better visibility for all parking facility users.

LIST OF FIGURES

Figure 1.	Types of injuries in parking lots and garages	5
Figure 2.	Percentages of crashes by type of maneuver	5
Figure 3.	Percentages of crashes by type of event	5
Figure 4.	Crashes involving pedestrians: percentage by type of maneuver	6
Figure 5.	Distribution of motor vehicle crashes in parking facilities	6
Figure 6.	Percentage of crashes by relation to junction variable	8
Figure 7.	Pre-incident maneuvers for parking lot crashes and near-crashes, nighttime condition	8
Figure 8.	Pre-incident maneuvers for crashes and near crashes, nighttime conditions	9
Figure 9.	Pre-incident maneuver for parking lot events, daytime conditions	9
Figure 10.	Percentages of precipitating events during nighttime conditions	9
Figure 11.	Precipitating events during nighttime conditions	10
Figure 12.	Distribution of event nature for crashes and near crashes at nighttime	10
Figure 13.	Event nature for crashes and near-crashes for nighttime conditions in parking lots and parking garages	10
Figure 14.	Event nature for parking lot crashes and near-crashes during daytime conditions	11
Figure 15.	Percentages of incidents in parking lot crashes, nighttime conditions	11
Figure 16.	Frequency of incidents in parking lots and parking garages during nighttime	11
Figure 17.	Percentages of incidents in parking lots and garages during daytime	11
Figure 18.	Percentages of driver behavior errors during crashes and near-crashes in parking lots and parking garages, nighttime conditions	12
Figure 19.	Driver behavior during crashes and near-crashes in parking lots and parking garages during daytime	12
Figure 20.	Safety-critical event classification for parking facilities	13
Figure 21.	List of critical visual tasks for drivers and pedestrians	15
Figure 22.	Wheel stops used in the detection task	18
Figure 23.	Facial recognition involved detection of glasses, (a) and (b). Hand recognition involved detection of hands, (a) and (c)	18
Figure 24.	Detection of a side-facing pedestrian	18
Figure 25.	Pedestrian detection at the stopping sight distance (SSD)	18
Figure 26.	Detection of a reversing vehicle	18
Figure 27.	Spectral power distributions of the three light sources used in the study	19
Figure 28.	Three light sources used in the parking garage experiment. These pictures are of equal luminance (average illuminance = 10 lux) and were captured with a calibrated photometer	19
Figure 29.	Three light sources used in the parking lot experiment. (Note: These pictures are not photometrically accurate.)	19
Figure 30.	Likert scale questionnaire used for perceptions of safety, comfort, and visibility	21

Figure 31.	Viewing a scene with a wheel stop and side-facing pedestrian (behind the vehicle) through the occlusion screen.	22
Figure 32.	Object locations for the pedestrian detection task.	23
Figure 33.	Scene of a detection task in the lot.	23
Figure 34.	Spectral power distribution of the halogen headlamps used in the study.	24
Figure 35.	Object locations for the driver detection task.	24
Figure 36.	Interactive effect of age, observer, light source type, and light level on detection probability in parking garages. Uppercase letters denote significant differences between light levels from pairwise comparisons ($p < 0.05$). Values are least-square means of estimated detection probability, and error bars represent standard errors.	27
Figure 37.	Effect of wheel stop color on detection probability for pedestrians and drivers at different distances.	27
Figure 38.	Effect of light level on perceptions of visibility, comfort, and safety. Uppercase letters denote significant differences from pairwise comparisons ($p < 0.05$). Values are least-square means of ratings of Likert composite scores, and error bars represent standard errors.	28
Figure 39.	Effect of light source type on perceptions of visibility, comfort, and safety. Uppercase letters denote significant differences from pairwise comparisons ($p < 0.05$). Values are least-square means of ratings of Likert composite scores, and error bars represent standard errors.	28
Figure 40.	Interactive effect of age, observer, light source type, and light level on detection. Uppercase letters denote significant differences between light levels from pairwise comparisons ($p < 0.05$). Values are least-square means of estimated detection probabilities, and error bars represent standard errors.	29
Figure 41.	Presence of a learning effect demonstrated by similar mean detection rates for participants who experienced HPS light source first vs. 5000-K LED first.	29
Figure 42.	Effect of wheel stop color on detection probabilities for pedestrians and drivers at different distances in the parking lot with asphalt pavement.	30
Figure 43.	Effect of light level on perceptions of visibility, safety, and comfort in the parking lot with asphalt pavement. Uppercase letters signify significant differences from pairwise comparisons ($p < 0.05$). Values are least-square means of ratings of Likert composite scores, and error bars represent standard errors.	31
Figure 44.	Effect of light source type on perceptions of visibility, safety, and comfort in the parking lot with asphalt pavement. Uppercase letters denote significant differences from pairwise comparisons ($p < 0.05$). Values are least-square means of ratings of Likert composite scores, and error bars represent standard errors.	31
Figure 45.	Interactive effects of age and light level on detection probability for pedestrians and drivers. Uppercase letters denote significant differences between light levels from pairwise comparisons ($p < 0.05$). Values are least-square means of estimated detection probabilities, and error bars represent standard errors.	31
Figure 46.	Effect of wheel stop color on detection probability for pedestrians and drivers at different distances in the parking lot with concrete pavement.	32
Figure 47.	Effect of light level on perceptions of visibility, safety, and comfort in the parking lot with concrete pavement. Uppercase letters signify significant differences from pairwise comparisons ($p < 0.05$). Values are least-square means of ratings of Likert composite scores, and error bars represent standard errors.	32

LIST OF TABLES

Table 1.	Increase in Recommended Maintained Horizontal Illuminance from RP-20-98 to RP-20-14.	1
Table 2.	Number of SHRP2 NDS Database Events at Parking Facilities	7
Table 3.	Number of Events within Parking Lot Boundaries, by Time of Day	8
Table 4.	Independent Variables and Their Levels	17
Table 5.	Critical Tasks in the Visual Performance Experiment.	19
Table 6.	Average Pavement Luminance Measurements (cd/m ²) for Pedestrians and Drivers in the Parking Garage, Taken at Various Illuminance Levels	20
Table 7.	Average Pavement Luminance Measurements (cd/m ²) for Pedestrians and Drivers in the Parking Lots, Taken at Various Illuminance Levels	20
Table 8.	Demographic Information of Participants in the Three Experiments	21
Table 9.	Statistical Results from the Repeated-Measures Logistic Regression Analysis for the Parking Garage. . .	26
Table 10.	Statistical Results from the LMM Analyses of Subjective Ratings for the Parking Garage	28
Table 11.	Statistical Results from the Repeated-Measures Logistic Regression Analysis for the Parking Lot with Asphalt Pavement	28
Table 12.	Statistical Results from the LMM Analyses of Subjective Ratings for the Parking Lot with Asphalt Pavement	30
Table 13.	Statistical Results from the Repeated-Measures Logistic Regression Analysis for the Parking Lot with Concrete Pavement.	31
Table 14.	Statistically Significant Results from the LMM Analyses of Subjective Ratings for the Parking Lot with Concrete Pavement.	32
Table 15.	Timeline of Project, Including Deliverables	41

1.0 Introduction

Lighting in parking lots and garages increases the visibility and sense of security for its users. The recommended light levels in parking lots and garages are included in the Illuminating Engineering Society’s Recommended Practice (RP-20) document for parking facilities. In the latest version (RP-20-14), the light levels recommended for parking lots were significantly higher than those mentioned in the previous version (RP-20-98). Some of the recommended illuminance levels are twice as high for parking lots with asphalt pavements and five times as high for parking lots with concrete pavements (see **Table 1**). The higher horizontal illuminance recommendations in RP-20-14 were likely based on consideration of a single critical task: detection of a non-painted concrete wheel stop on a concrete pavement. However, this critical task only accounts for the detection of trip hazards by pedestrians and ignores the other critical interactions between vehicles and pedestrians. Moreover, detection of a wheel stop whose texture and color are very similar to the surface on which it is placed requires a much higher luminance contrast. Higher luminance contrasts could be obtained by increasing the illuminance of the pavement in the parking lots (Adrian, 1989; Pretto & Chatziastros, 2006).

Table 1. Increase in Recommended Maintained Horizontal Illuminance from RP-20-98 to RP-20-14

	Pavement Type	RP-20-98	RP-20-14	Increase in Illuminance
Basic	All	2 lux		
Enhanced	All	5 lux		
Pre-curfew	Asphalt		5 lux	2.5 times
	Concrete		10 lux	5 times
Post-curfew	Asphalt		2 lux	
	Concrete		2 lux	

It is noteworthy, however, that an increase in illuminance will typically increase visibility only until a plateau is reached; beyond that plateau, any increase in illuminance will not result in an increase in visibility (Adrian, 1989; Bhagavathula, 2016; Bhagavathula, Gibbons, & Nussbaum, 2017; Rea & Ouellette, 1991). The additional illuminance can not only result in energy waste, but may also create conditions that increase discomfort glare and disability glare for parking lot users. In order to determine parking lot illuminance levels that increase visibility as well as parking lot users’ perceptions of comfort, safety, and visibility, while still conserving energy and reducing glare, it is important to determine critical tasks that are realistic and account for all possible parking lot users and their interactions.

As noted, the two major users of parking facilities are pedestrians and drivers, and therefore the critical tasks for determining the lighting requirements for parking lots and garages should involve both types of user. There are three major tasks that involve both types of parking lot and parking garage users:

- Driver-pedestrian and other driver interactions
- Pedestrian and driver obstacle detection and navigation
- Pedestrian and driver perceptions of comfort, safety, and visibility

If these critical tasks were to be taken into consideration, lighting requirements for parking lots and garages could be developed to increase the visibility and perceptions of comfort, safety, and visibility for all users.

Crash statistics in parking lots have seldom been analyzed. In a study in Montgomery County, Maryland, pedestrian-vehicle crashes accounted for about 23% of the total crashes in a 5-year period (2004 to 2009). This data