US Department of Energy Solid State Lighting R&D Workshop

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WSP

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I'm a Lighting Designer…

Somebody Please Help me!

Balancing Performance, Safety, Energy, Health, and Environmental Impacts of Roadway Lighting

Solid State Lighting has raised a number of questions for lighting designers

- Does it work as well as current HID technologies?
- Are design methods and criteria currently used applicable to this technology?
- Are there unforeseen impacts of the technology?
- Are there unforeseen benefits of the technology?

Possible Health Impacts of SSL Technologies?

Health Impacts

Bright Lights, Big Risk for Breast Cancer

Nocturnal illumination may be suppressing a cancer-fighting hormone.

BY CATHERINE GUTHRIE

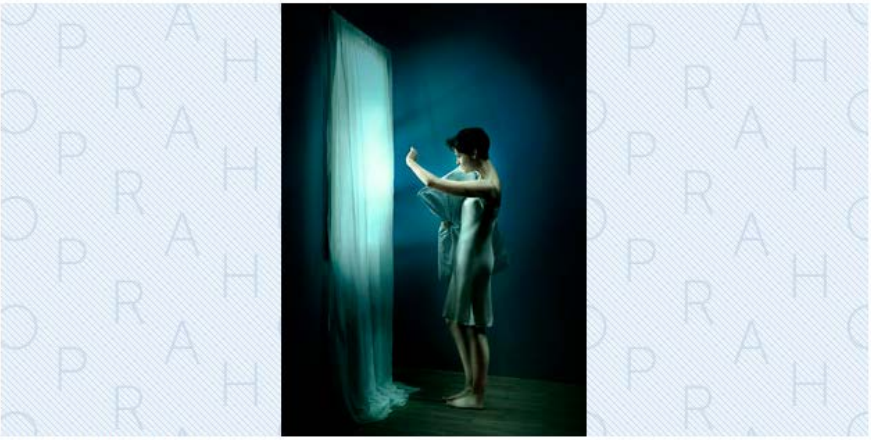

PHOTO: JONATHAN BARKAT

Example of misinterpreted research

"We've just learned that the streetlight shining in your bedroom window every night is not only annoying; it may be jacking up your risk of breast cancer...."

AMA Adopts Guidance to Reduce Harm from High Intensity Street Lights

For immediate release: Jun 14, 2016

AMA Report

- AMA has stated –
  - Use 3000k
    - Reduces Sky Glow
    - Reduces impact in Humans
    - Reduces impact on Migratory Animals
    - Reduces impact on Sea Turtles
    - Etc.
- Is this justified with research?

IES Response

- Given the state of current knowledge, it is not possible to weigh the probabilities of health care concerns regarding light-at-night and its effect on sleep disruption from outdoor and roadway lighting against the needs of nighttime driver and pedestrian safety, but such deliberations should precede any policy statement that affects both concerns.
- Correlated Color Temperature (CCT) is inadequate for the purpose of evaluating possible health outcomes; and that the recommendations target only one component of light exposure (spectral composition) of what are well known and established multi-variable inputs to light dosing that affect sleep disruption, including the quantity of light at the retina of the eye and the duration of exposure to that light.
- A more widely accepted input to the circadian system associated with higher risk for sleep disruption and associated health concerns is increased melanopic content, which is significantly different than CCT.
- The upper CCT limit of 3000 K contained in AMA Policy H-135.927 lacks scientific foundation and does not assure the public of any certainty of health benefit or risk avoidance.

Impacts (Dosage and Duration)

PNNL data

Combined subset* of readings taken by Naomi Miller, Bruce Kinzey, Rita Koltai, Terry McGowan, Derry Berrigan (*note: not all participants provided readings in every category; not all categories listed)	Reading (Lux)
Vert illuminance from window facing street light, if avail., interior lights off	
-- blinds open	≤0.1
-- blinds closed	0
Vert illuminance from window not facing street light	0-1
Kitchen	30-340
TV from 10 feet away, room light off	0-10
TV from 10 feet away, room light on	2-30
Phone/tablet at reading distance, other room lighting off	0-5
Phone/tablet at reading distance, room lighting on	15-45
Bedside lamp(s) reflecting on magazine/book page	35-350
Max horizontal illuminance at street light nadir - no vegetation interference	5-10
Max horizontal illuminance at street light nadir - some interference	0-5

Measuring and using light in the melanopsin age

Robert J. Lucas[1*], Stuart N. Peirson[2*], David M. Berson[3], Timothy M. Brown[1], Howard M. Cooper[4], Charles A. Czeisler[5], Mariana G. Figueiro[6], Paul D. Gamlin[7], Steven W. Lockley[5], John B. O'Hagan[8], Luke L.A. Price[8], Ignacio Provencio[9], Debra J. Skene[10], and George C. Brainard[11]

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[3] Department of Neuroscience, Brown University, Box G-LN, Providence, RI, USA
[4] INSERM 846 Stem Cell and Brain Research Institute, Department of Chronobiology, 18 Avenue du Doyen Lépine, 69500 Bron, France
[5] Division of Sleep Medicine, Harvard Medical School, and Division of Sleep Medicine, Department of Medicine, Brigham and Women's Hospital, Boston, MA, USA
[6] Lighting Research Center, Rensselaer Polytechnic Institute, Troy, NY 12180, USA
[7] Department of Ophthalmology, University of Alabama at Birmingham, Birmingham, AL 35294, USA
[8] Public Health England, Chilton, Didcot OX11 0RQ, UK
[9] Department of Biology, University of Virginia, Charlottesville, VA, USA
[10] Faculty of Health and Medical Sciences, University of Surrey, Guildford GU2 7XH, UK
[11] Department of Neurology, Thomas Jefferson University, Philidelphia, PA, USA

(Trends in Neurosciences, January 2014, Vol. 37, No. 1)

Irradiance Toolbox

Title HPS 100W

Chart input Pigment: Melanopic | Page 1

1) Select mode 5nm spectral data

i. Enter spectral power distribution in column AH
ii. Check using the chart opposite that the data is 5nm resolution
iii. Skip sections 2 and 3: these inputs are not applicable in this mode

2) Details of light measurement

Light source	A	n/a
Units	L	n/a
Amount	100.00	n/a

3) For blackbody or narrowband sources

Blackbody temperature	4200	n/a		
Narrowband peak	420	n/a		nm
Narrowband FWHM	42	n/a	Peak spectral irradiance	600

4) Photopic illuminance

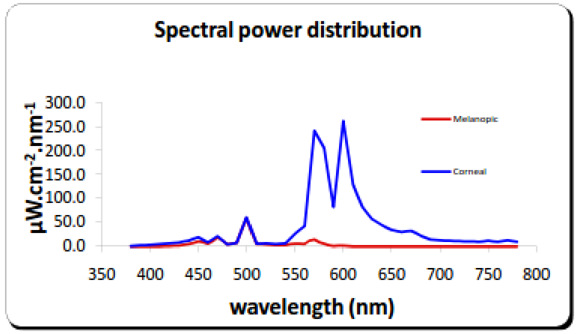
Optional prefix	Sensitivity	λ_{max}	Subscript	Curve	lux
Photopic	Visibility	555.0	n/a	V(λ)	11,904.27

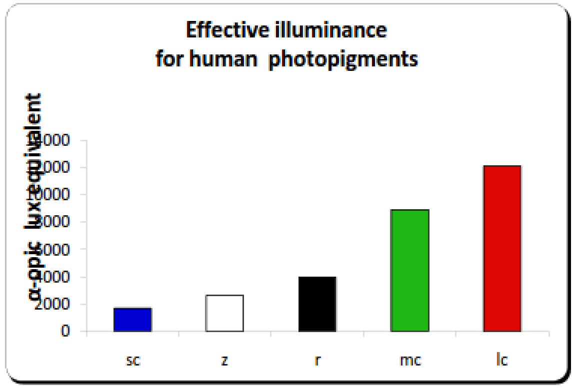
5) Human retinal photopigment complement (all weighted)

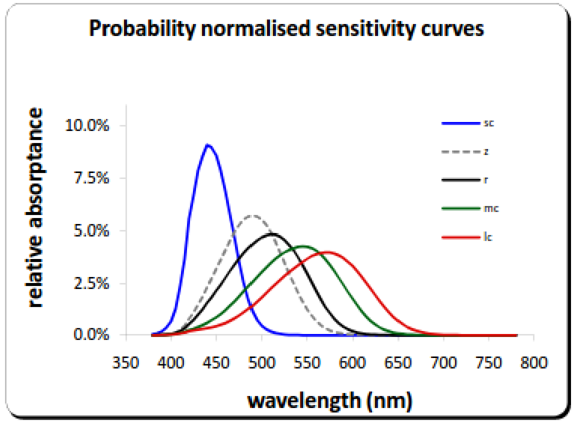
Prefix	Sensitivity	λ_{max}	α in $N_{\alpha}(\lambda)$	Curve	α-opic lux
Cyanopic	S cone	419.0	sc	$N_{sc}(\lambda)$	1,700.58
Melanopic	Melanopsin	480.0	z	$N_{z}(\lambda)$	2,647.27
Rhodopic	Rod	496.3	r	$N_{r}(\lambda)$	3,969.21
Chloropic	M cone	530.8	mc	$N_{mc}(\lambda)$	8,920.17
Erythropic	L cone	558.4	lc	$N_{lc}(\lambda)$	12,080.54

6) Unweighted summations from 380 to 780 nm inclusive

Quantity	Units	Amount
Irradiance	$\mu W/cm^2$	3,154.16
Photon flux	$1/cm^2/s$	9.43E+15
Log photon flux	$\log_{10}(1/cm^2/s)$	15.97







http://www.ndcn.ox.ac.uk/team/stuart-peirson/downloadstile-14/filetile-3/@@download

Irradiance Toolbox

Title Cree 4000K 68 watts

Chart input **Pigment** Melanopic

1) Select mode 5nm spectral data

i. Enter spectral power distribution in column AH
ii. Check using the chart opposite that the data is 5nm resolution
iii. Skip sections 2 and 3: these inputs are not applicable in this mode

2) Details of light measurement

Light source	A	n/a
Units	L	n/a
Amount	100.00	n/a

3) For blackbody or narrowband sources

				nm
Blackbody temperature	4200	n/a		
Narrowband peak	420	n/a		
Narrowband FWHM	42	n/a	Peak spectral irradiance	460

4) Photopic illuminance

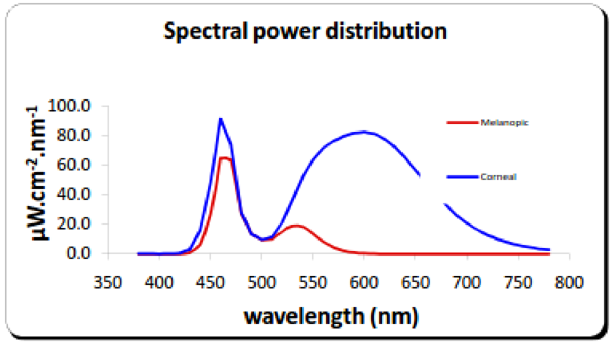
Optional prefix	Sensitivity	λ_{max}	Subscript	Curve	lux
Photopic	Visibility	555.0	n/a	V(λ)	8,549.31

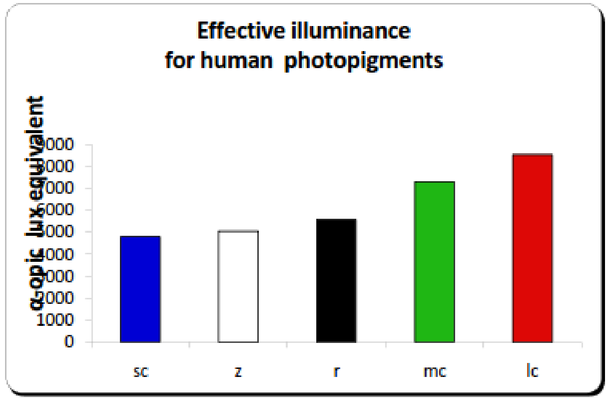
5) Human retinal photopigment complement (all weighted)

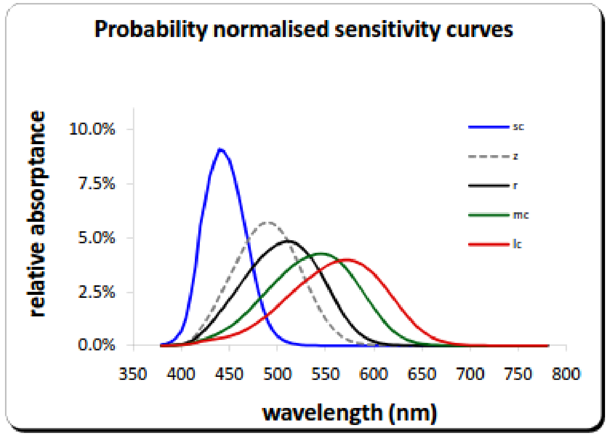
Prefix	Sensitivity	λ_{max}	α in $N_{\alpha}(\lambda)$	Curve	α-opic lux
Cyanopic	S cone	419.0	sc	$N_{sc}(\lambda)$	4,797.11
Melanopic	Melanopsin	480.0	z	$N_{z}(\lambda)$	5,049.75
Rhodopic	Rod	496.3	r	$N_{r}(\lambda)$	5,573.58
Chloropic	M cone	530.8	mc	$N_{mc}(\lambda)$	7,293.88
Erythropic	L cone	558.4	lc	$N_{lc}(\lambda)$	8,529.20

6) Unweighted summations from 380 to 780 nm inclusive

Quantity	Units	Amount
Irradiance	μW/cm²	2,881.02
Photon flux	1/cm²/s	8.43E+15
Log photon flux	$\log_{10}$ (1/cm²/s)	15.93







Irradiance Toolbox

Title	Cree 3000K 57W		Chart input	Pigment	Melanopic	Page 1

1) Select mode — 5nm spectral data

i. Enter spectral power distribution in column AH
ii. Check using the chart opposite that the data is 5nm resolution
iii. Skip sections 2 and 3: these inputs are not applicable in this mode

2) Details of light measurement

Light source	A	n/a
Units	L	n/a
Amount	100.00	n/a

3) For blackbody or narrowband sources

Blackbody temperature	4200	n/a		
Narrowband peak	420	n/a		nm
Narrowband FWHM	42	n/a	Peak spectral irradiance	600

4) Photopic illuminance

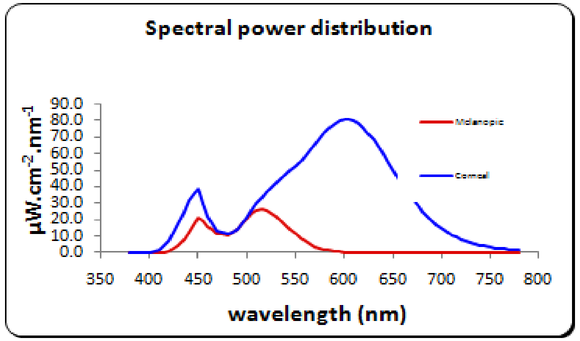
Optional prefix	Sensitivity	l_{max}	Subscrip	Curve	lux
Photopic	Visibility	555.0	n/a	V(λ)	8,097.51

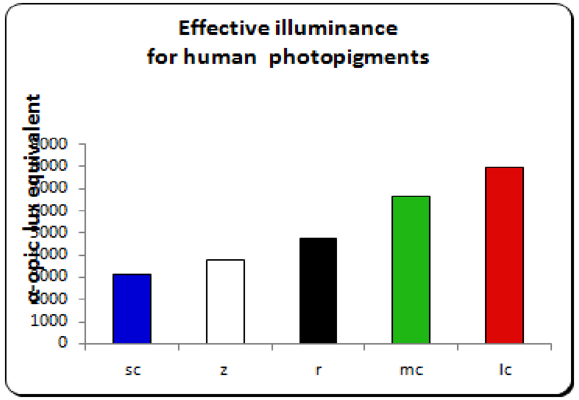
5) Human retinal photopigment complement (all weighted)

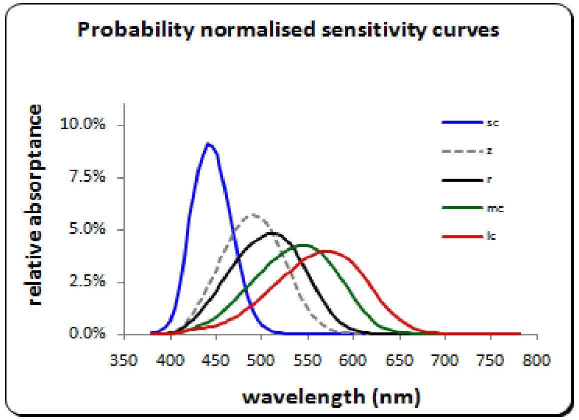
Prefix	Sensitivity	l_{max}	α in $N_α$(λ	Curve	α-opic lux
Cyanopic	S cone	419.0	sc	$N_{sc}(λ)$	3,109.38
Melanopic	Melanopsin	480.0	z	$N_z(λ)$	3,789.03
Rhodopic	Rod	496.3	r	$N_r(λ)$	4,734.09
Chloropic	M cone	530.8	mc	$N_{mc}(λ)$	6,678.76
Erythropic	L cone	558.4	lc	$N_{lc}(λ)$	7,970.95

6) Unweighted summations from 380 to 780 nm inclusive

Quantity	Units	Amount
Irradiance	$\mu W/cm^2$	2,496.44
Photon flux	$1/cm^2/s$	7.32E+15
Log photon flux	$\log_{10}(1/cm^2/s)$	15.86







Here is what we know and don’t know

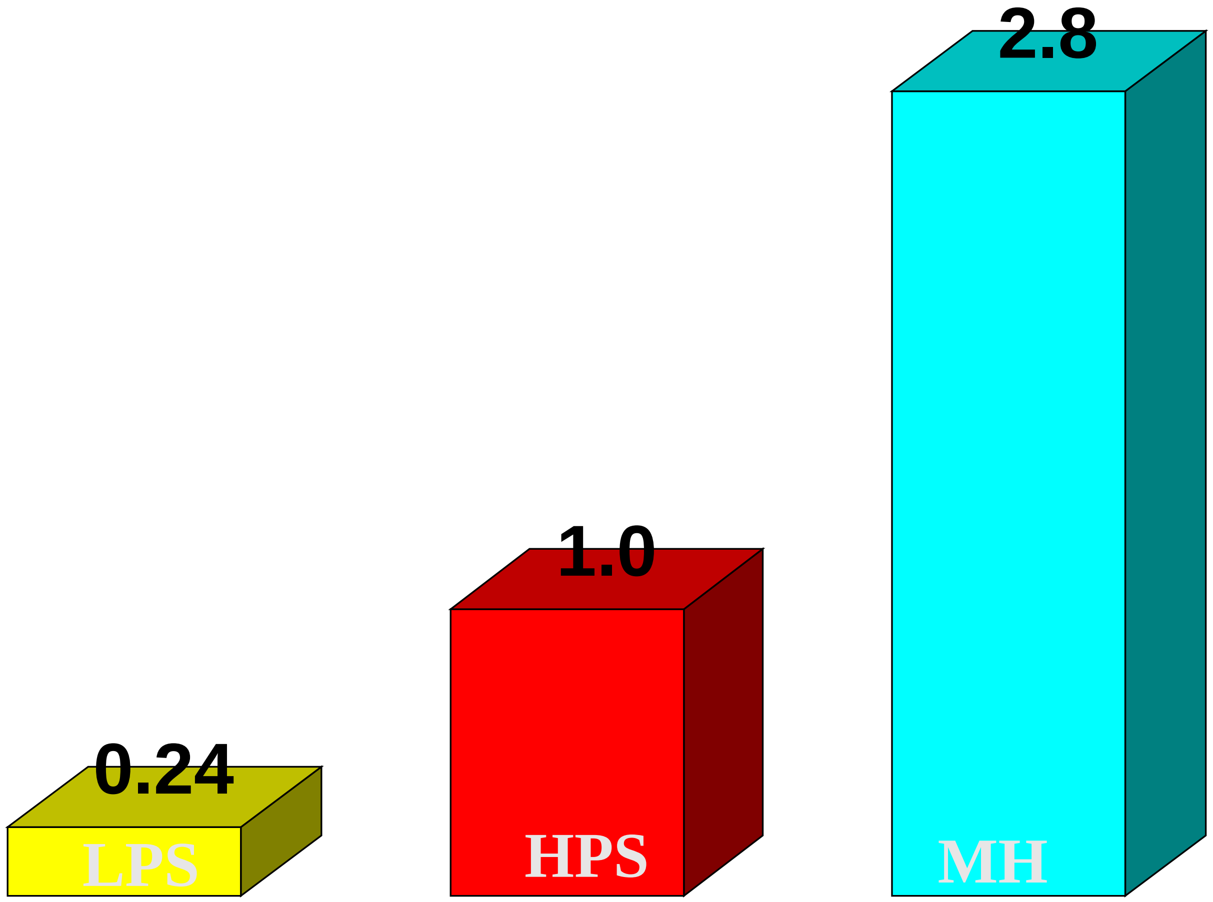
- Light at night has a physiological effect.
- Severity of the effect depends upon spectral content and dosage.
- We don’t know if future research will show well designed streetlighting has an impact on health but current research doesn’t seem to indicate that.
- We need to have a spectrally weighted limit on dosage from streetlighting.

Possible Impacts to the Environment?

Sky Glow

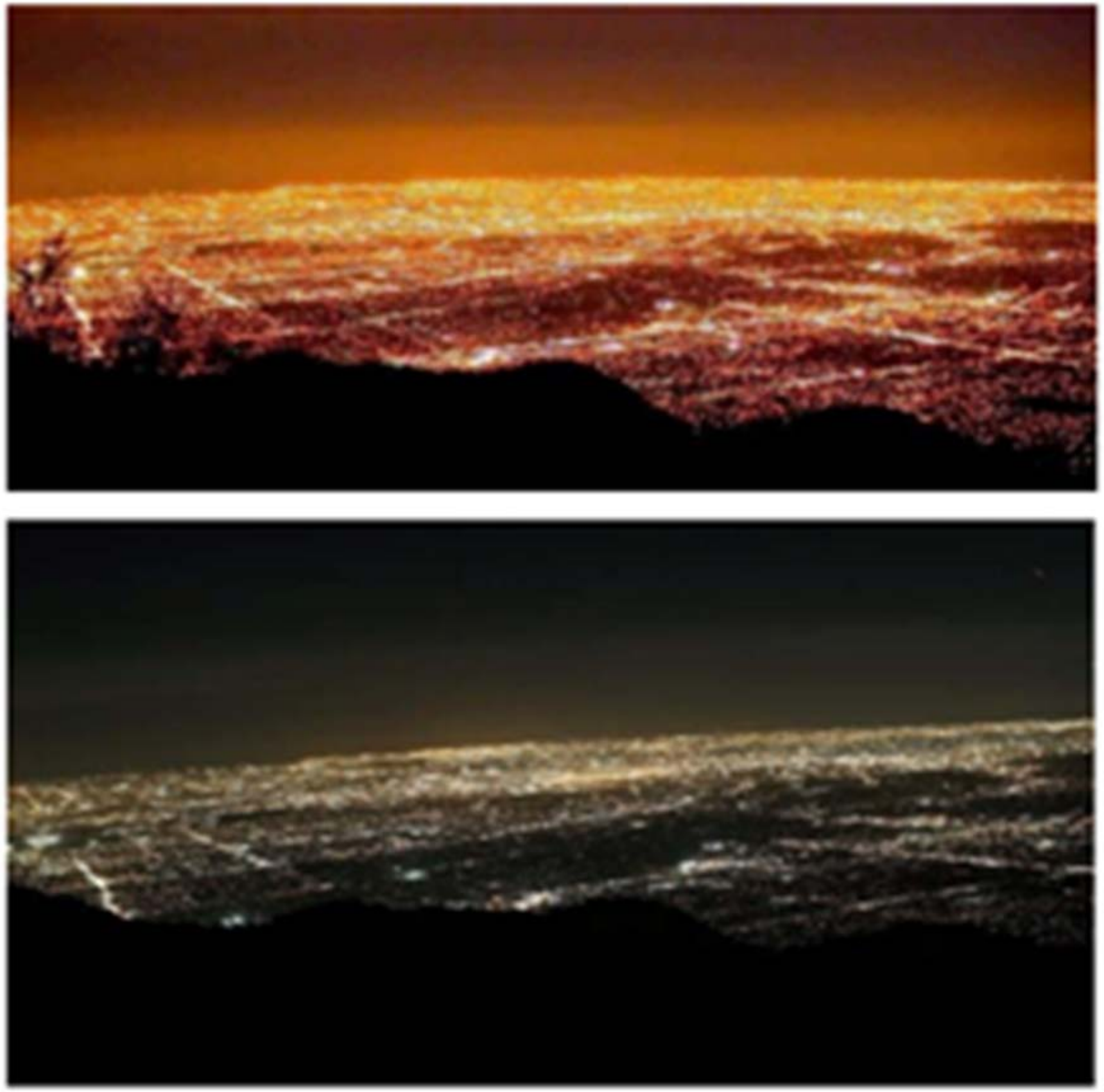
- Sky Glow
  - Blue Light Scatters more than amber light
- Rayleigh Scattering
  - Molecular Scattering – Molecule are about the same size as the wavelength for blue light
  - Blue Light Scatters more
  - Low angle blue content light is particularly bad
- Mie Scattering
  - Aerosol Scattering – Particles are much bigger than wavelength
  - Not Spectrally Selective

Relative Sky Glow



From CORM 2008, Luginbuhl, Keith & Knox

Sky Glow

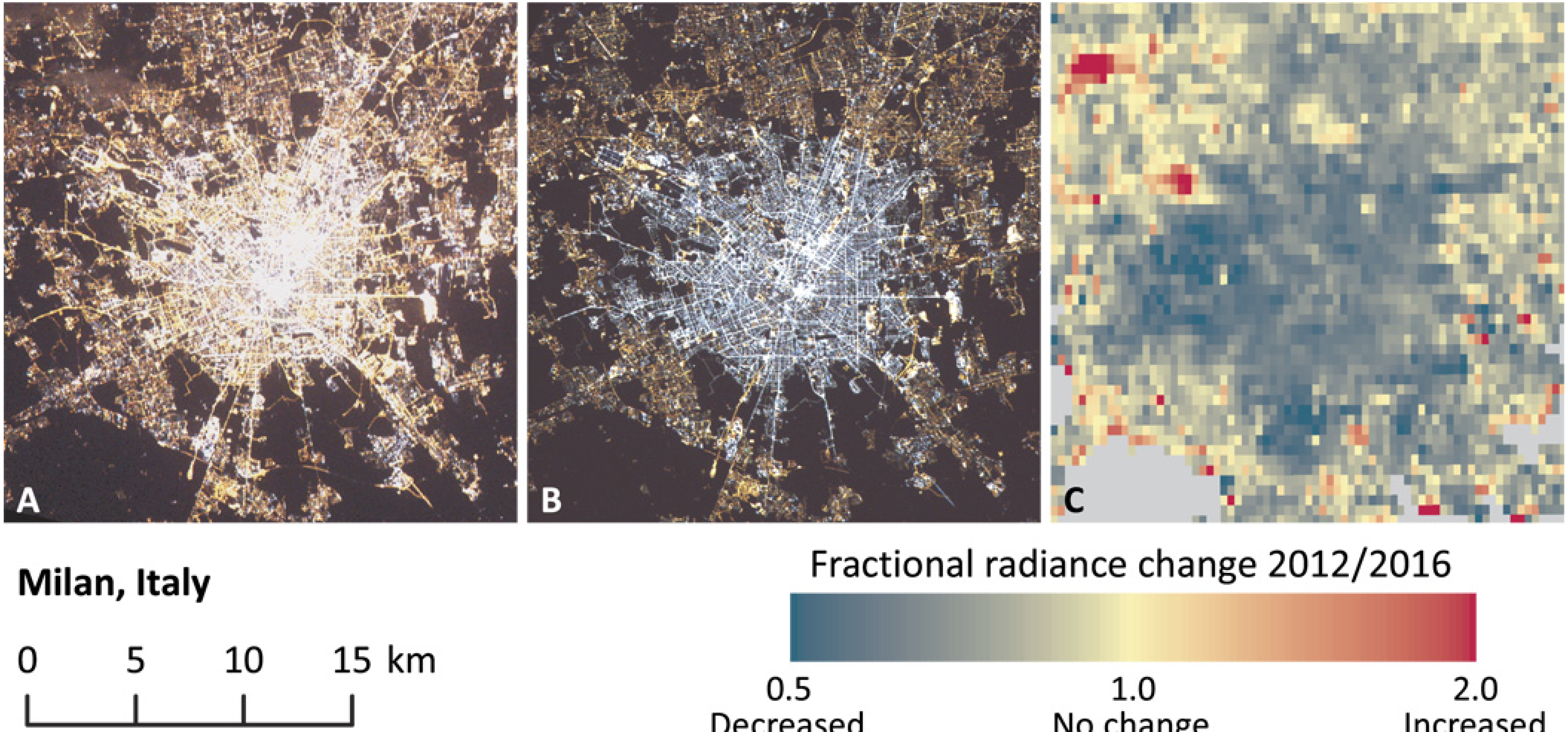


View from Mt Wilson of light pollution in Los Angeles, before and after LED deployment

Artificially lit surface of Earth at night increasing in radiance and extent

Christopher C. M. Kyba,[1,2]* Theres Kuester,[1] Alejandro Sánchez de Miguel,[3,4†] Kimberly Baugh,[5] Andreas Jechow,[1,2] Franz Hölker,[2] Jonathan Bennie,[6] Christopher D. Elvidge,[7] Kevin J. Gaston,[8] Luis Guanter[1]

A central aim of the "lighting revolution" (the transition to solid-state lighting technology) is decreased energy consumption. This could be undermined by a rebound effect of increased use in response to lowered cost of light. We use the first-ever calibrated satellite radiometer designed for night lights to show that from 2012 to 2016, Earth's artificially lit outdoor area grew by 2.2% per year, with a total radiance growth of 1.8% per year. Continuously lit areas brightened at a rate of 2.2% per year. Large differences in national growth rates were observed, with lighting remaining stable or decreasing in only a few countries. These data are not consistent with global scale energy reductions but rather indicate increased light pollution, with corresponding negative consequences for flora, fauna, and human well-being.



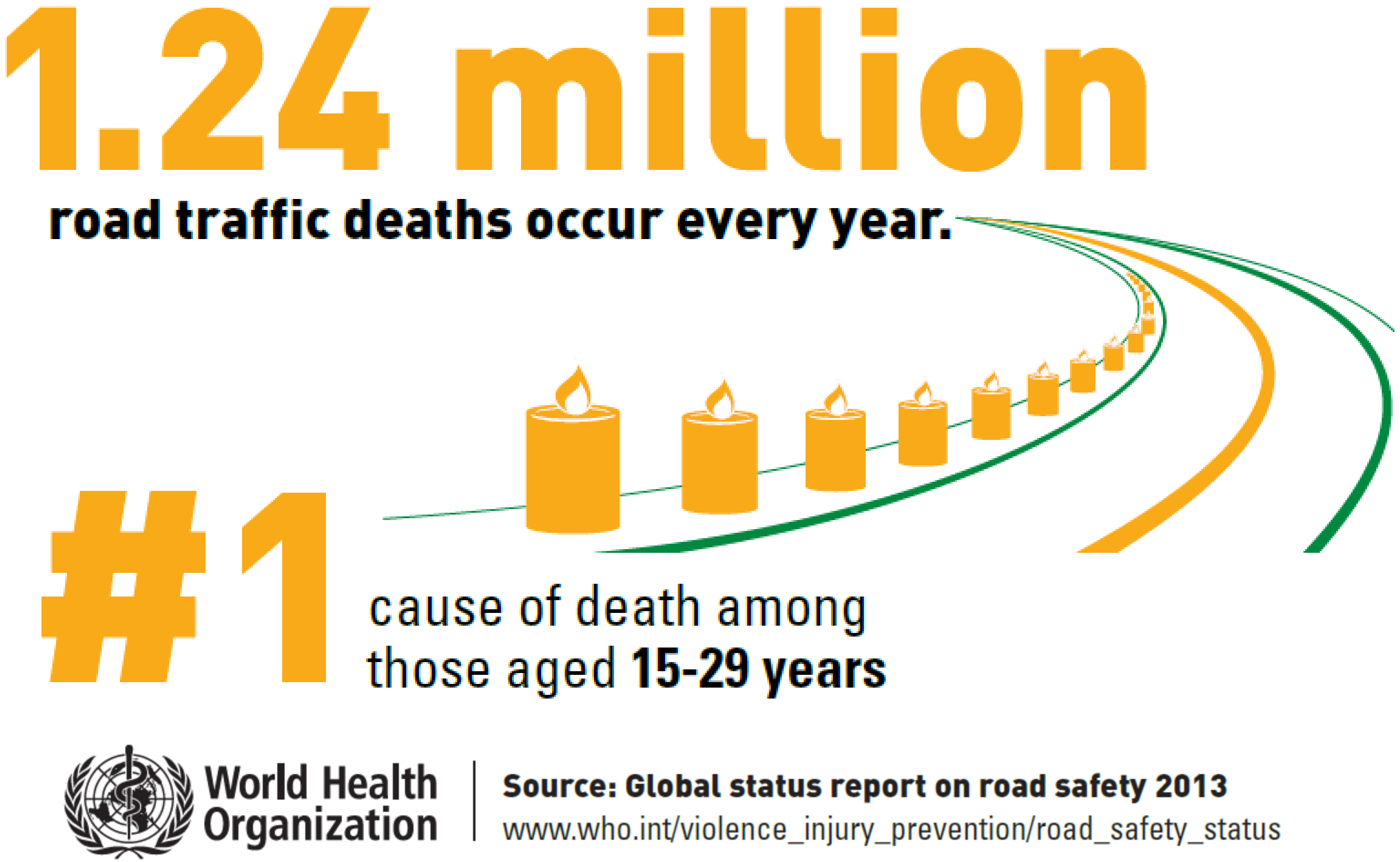
http://advances.sciencemag.org/content/3/11/e1701528

Here is what we know and don’t know

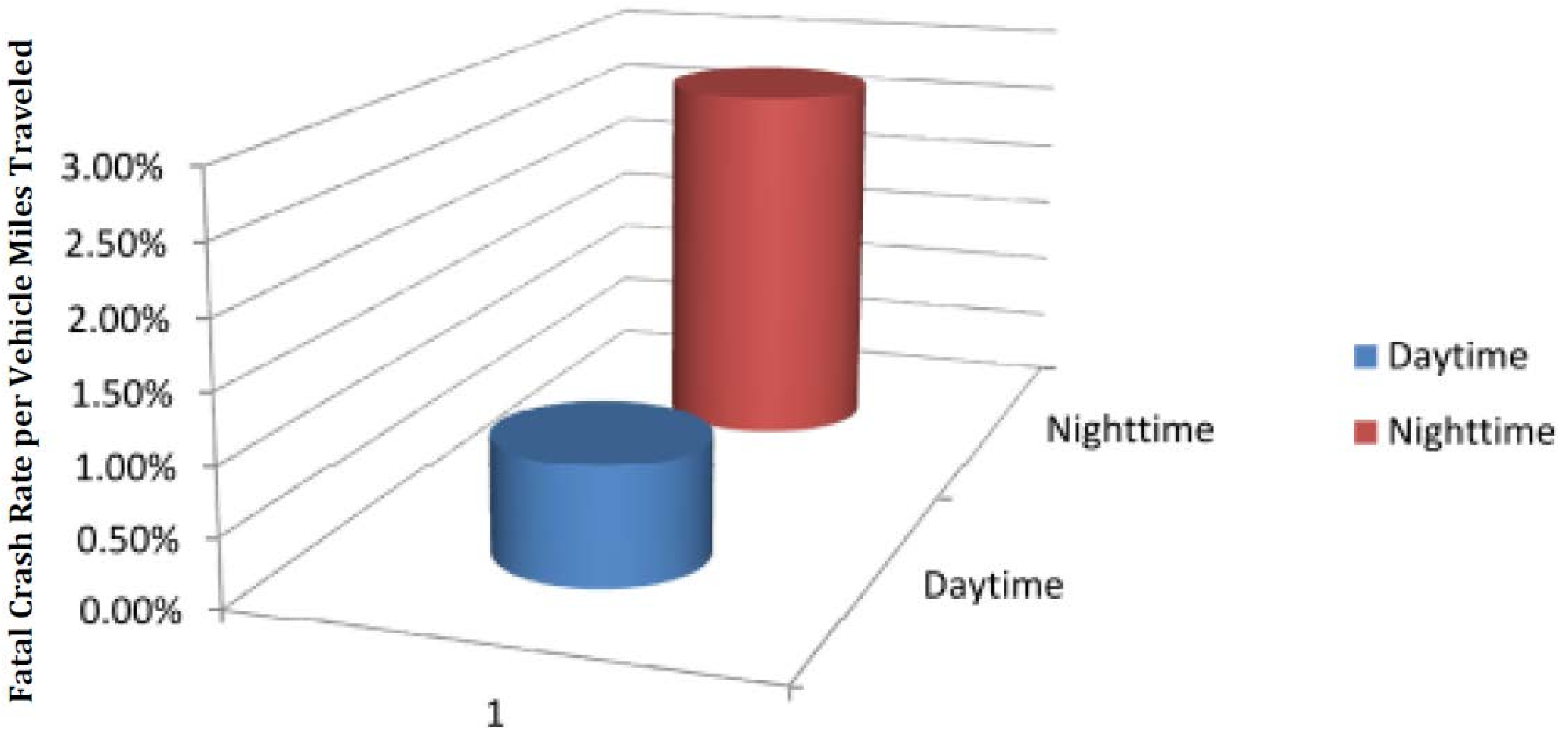
- Light at night can effect plants and animals
- Exterior lighting creates sky glow
- Different spectral content sources have different impacts
- We don’t have a good method of quantifying impacts in terms of lighting output, direction, and spectral weighting

Possible Safety Impacts?

Safety - Global Traffic Fatalities



Fatal Crash Rate Daytime and Nighttime



Fatal Crashes Lighting vs No Lighting

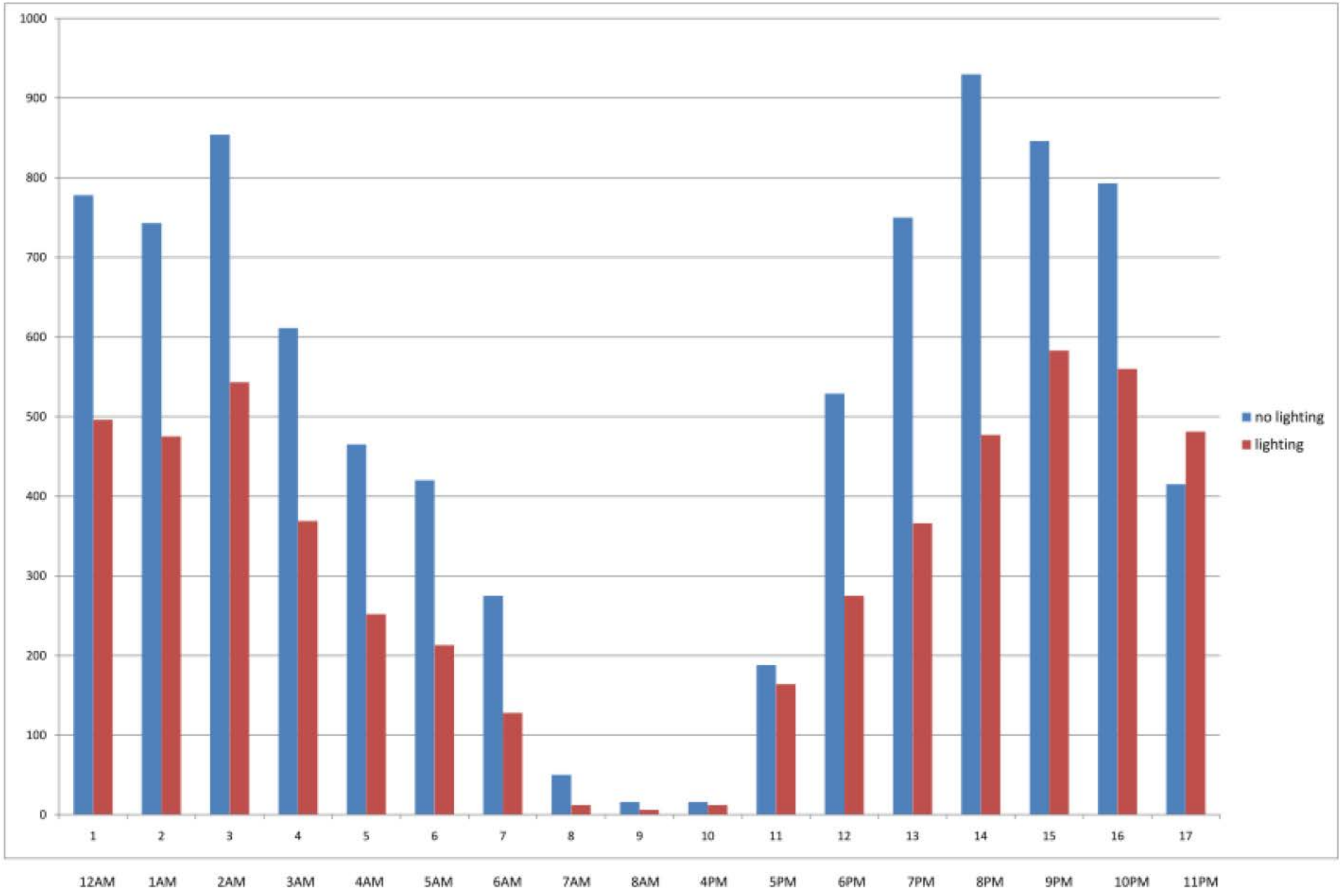
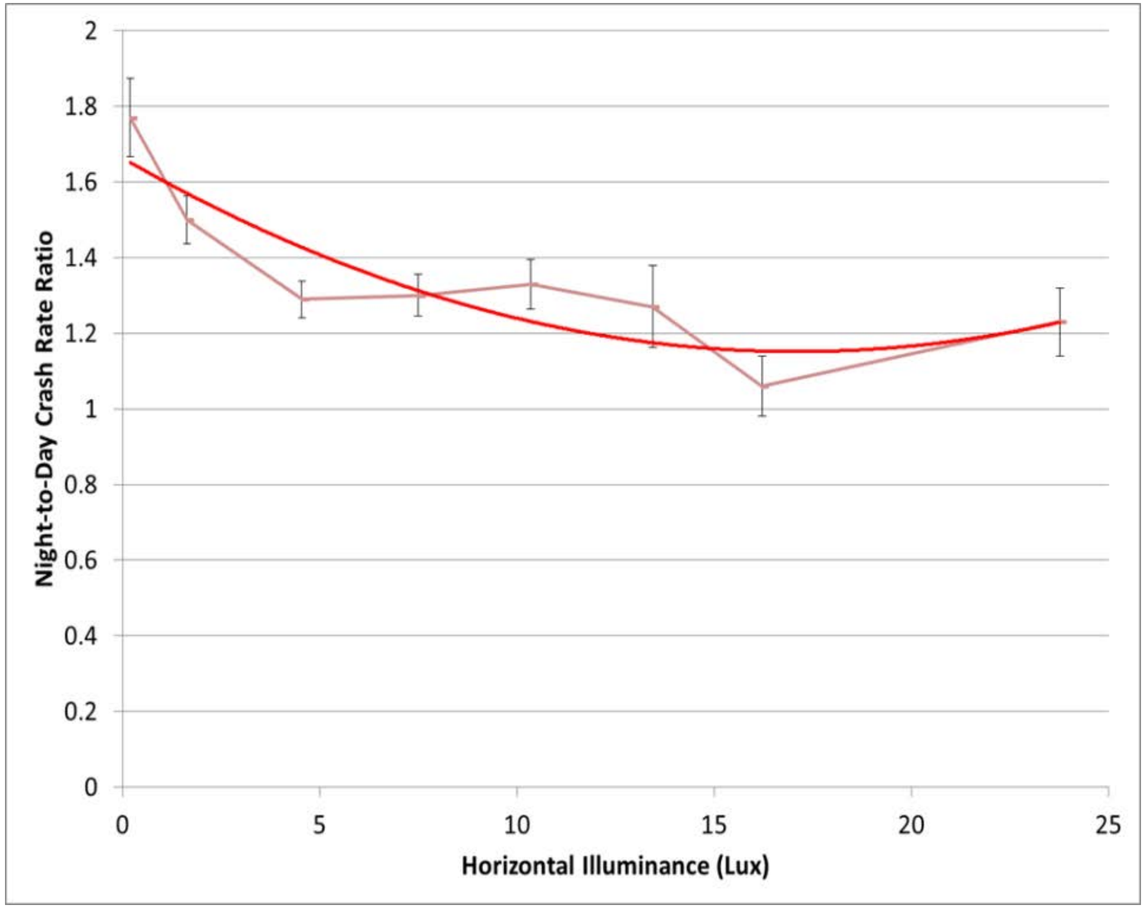


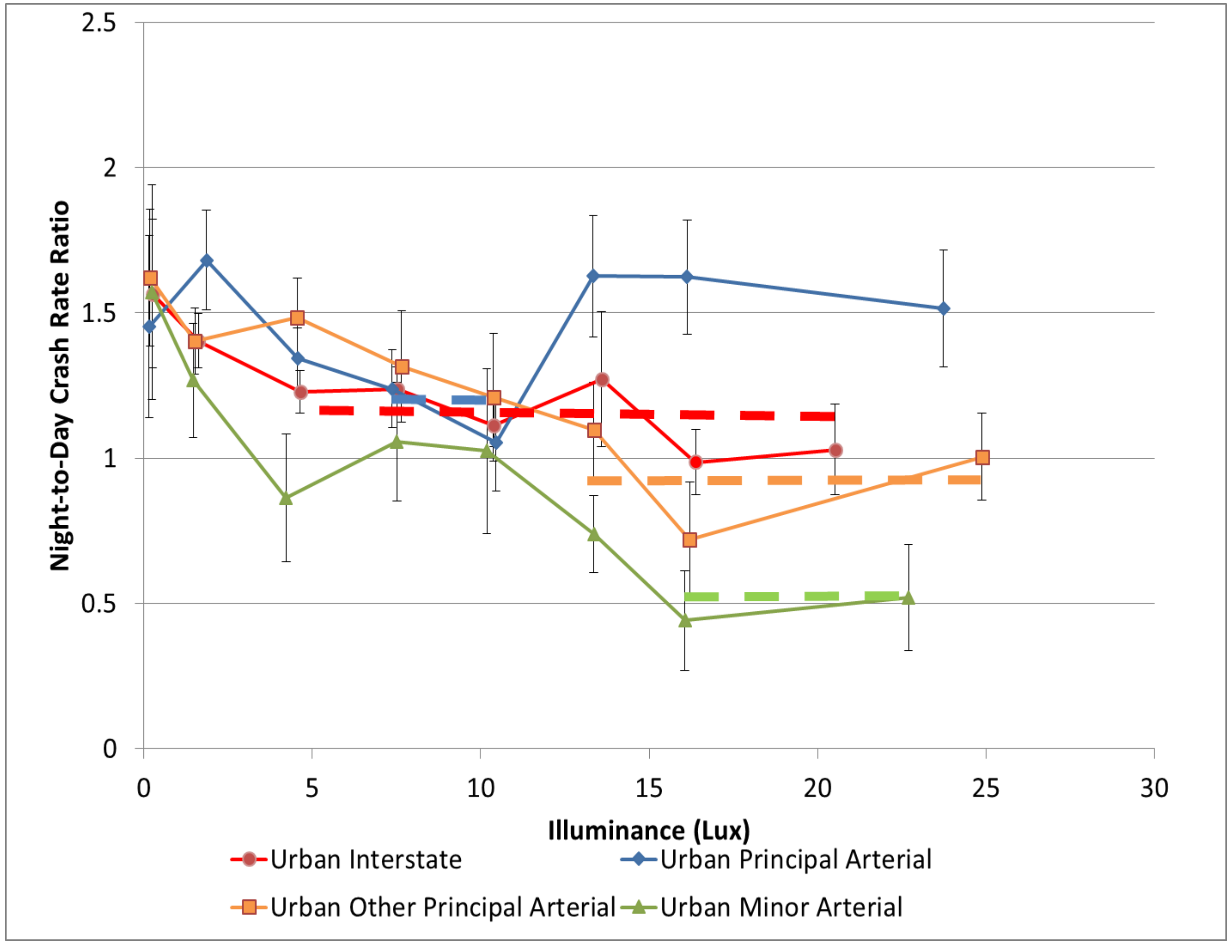
Figure 1b - Fatal Crashes during Darkness by Lighting Condition (2009 FARS data)

Safety - Effect of Lighting on Crashes

Conditions		Effect	95 % conf.
All		-54 %	-56 %, -52 %
Weather conditions	Fine weather	-54 %	-56 %, -52 %
	Rainy weather	-45 %	-53 %, -37 %
	Foggy conditions	0 %	-15 %, +18 %
	Snowy weather	-26 %	-40 %, +8 %
Road surface conditions	Dry road surface	-56 %	-59 %, -54 %
	Wet road surface	-46 %	-50 %, -43 %
	Snow / ice covered	-22 %	-31 %, -11 %
Road user	Pedestrian	-70 %	-77 %, -61 %
	Bicycle	-60 %	-65 %, -54 %
	Moped	-61 %	-64 %, -56 %
	MC	-26 %	-42 %, -5 %
	Automobile	-50 %	-52 %, -47 %
Accident type	Hit fixed object	-54 %	-58 %, -49 %
	Frontal collisions	-50 %	-55 %, -43 %
	Flank collisions	-46 %	-51 %, -41 %
	Hit animal	-57 %	-63 %, -50 %
	Rear end collisions	-51 %	-54 %, -46 %

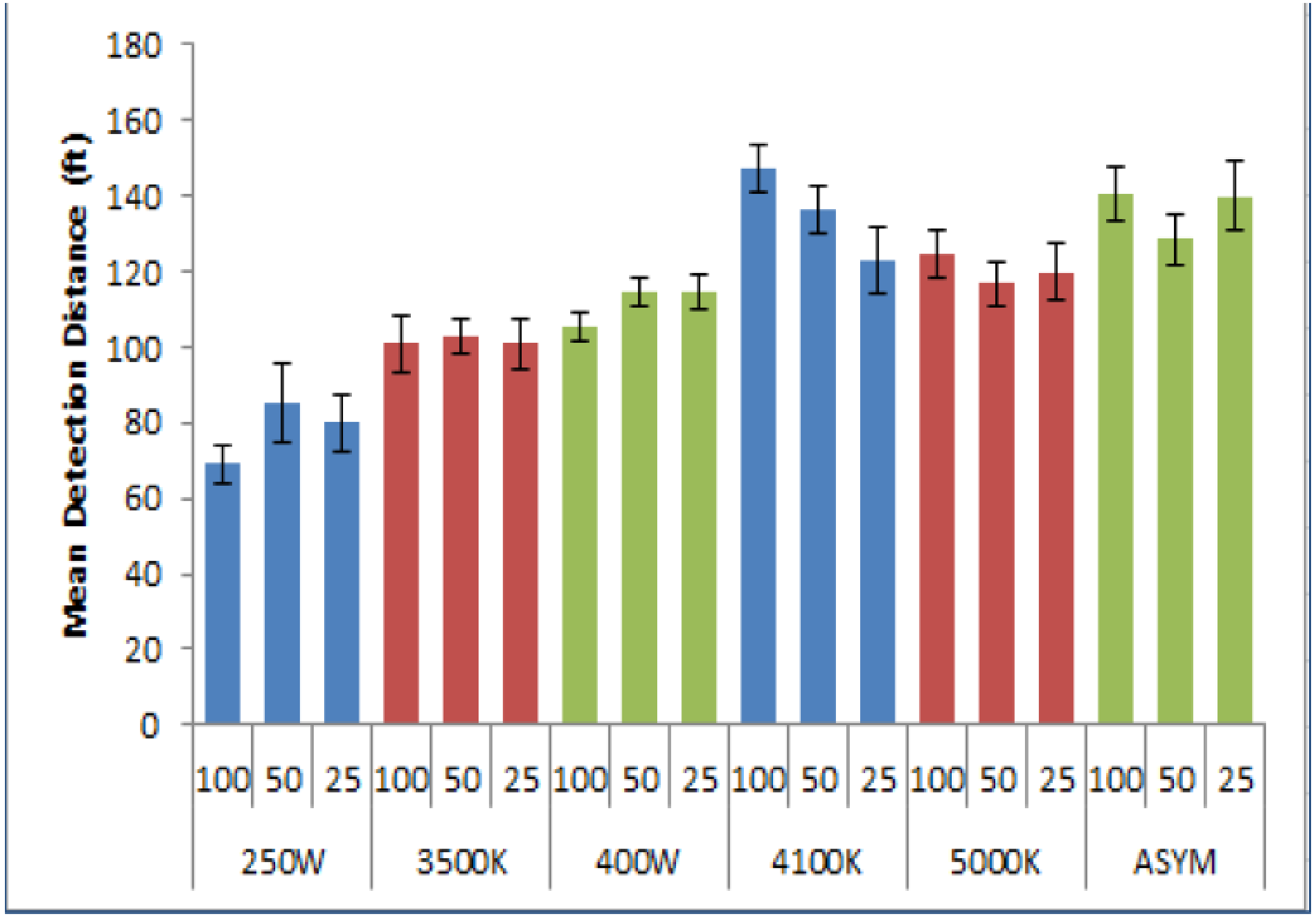
Research by Per Ole Wanvik – Road Lighting and Traffic Safety



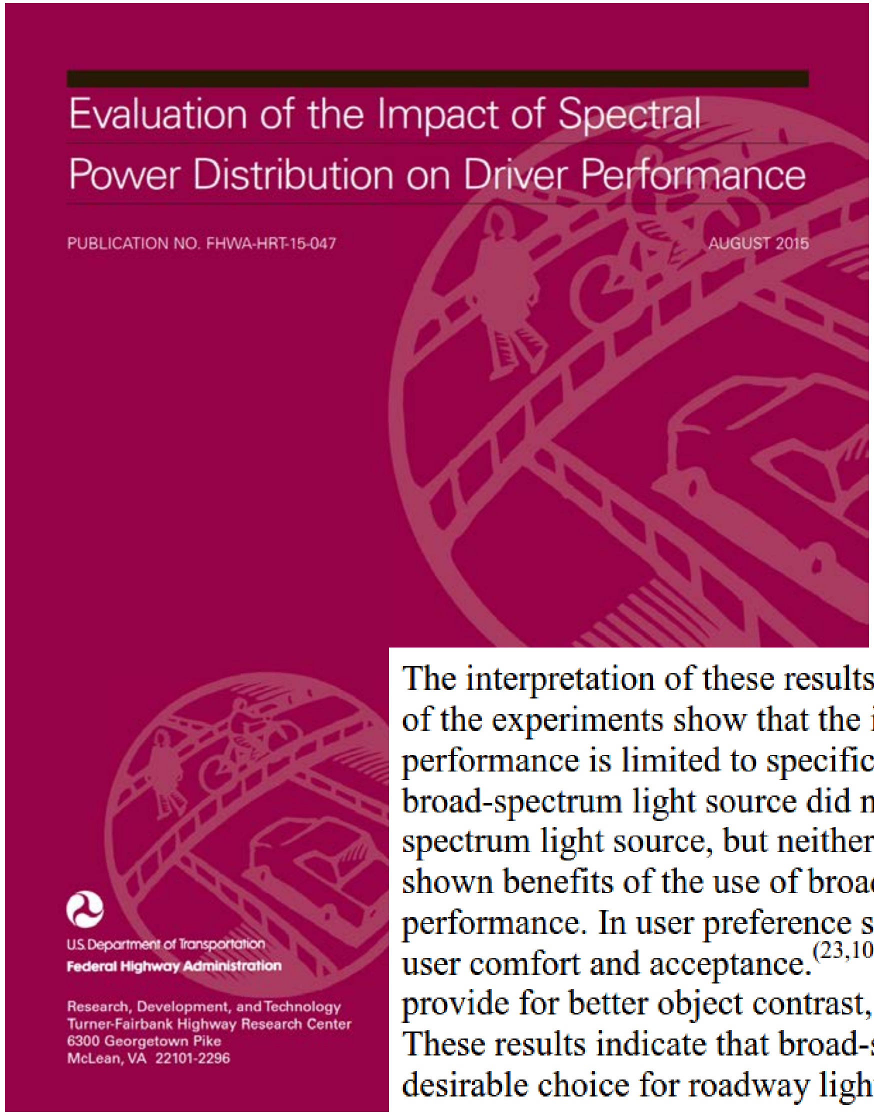


https://www.fhwa.dot.gov/publications/research/safety/14050

Color Contrast



https://neea.org/docs/default-source/reports/seattle-led-adaptive-lighting-study.pdf?sfvrsn=4



The interpretation of these results is an important aspect of this project. As mentioned, the results of the experiments show that the impact of overhead lighting spectrum on driver visual performance is limited to specific situations. It is important to note that, in many situations, the broad-spectrum light source did not improve driver visual performance over the narrow-spectrum light source, but neither did it worsen driver visual performance. Other studies have shown benefits of the use of broad-spectrum light sources beyond providing better visual performance. In user preference studies, broad-spectrum light sources were preferred for their user comfort and acceptance.[23,101] Other research has shown that broad-spectrum sources provide for better object contrast, thus increasing the detection of objects along the roadside. These results indicate that broad-spectrum lighting is a valid choice in general and likely a desirable choice for roadway lighting.

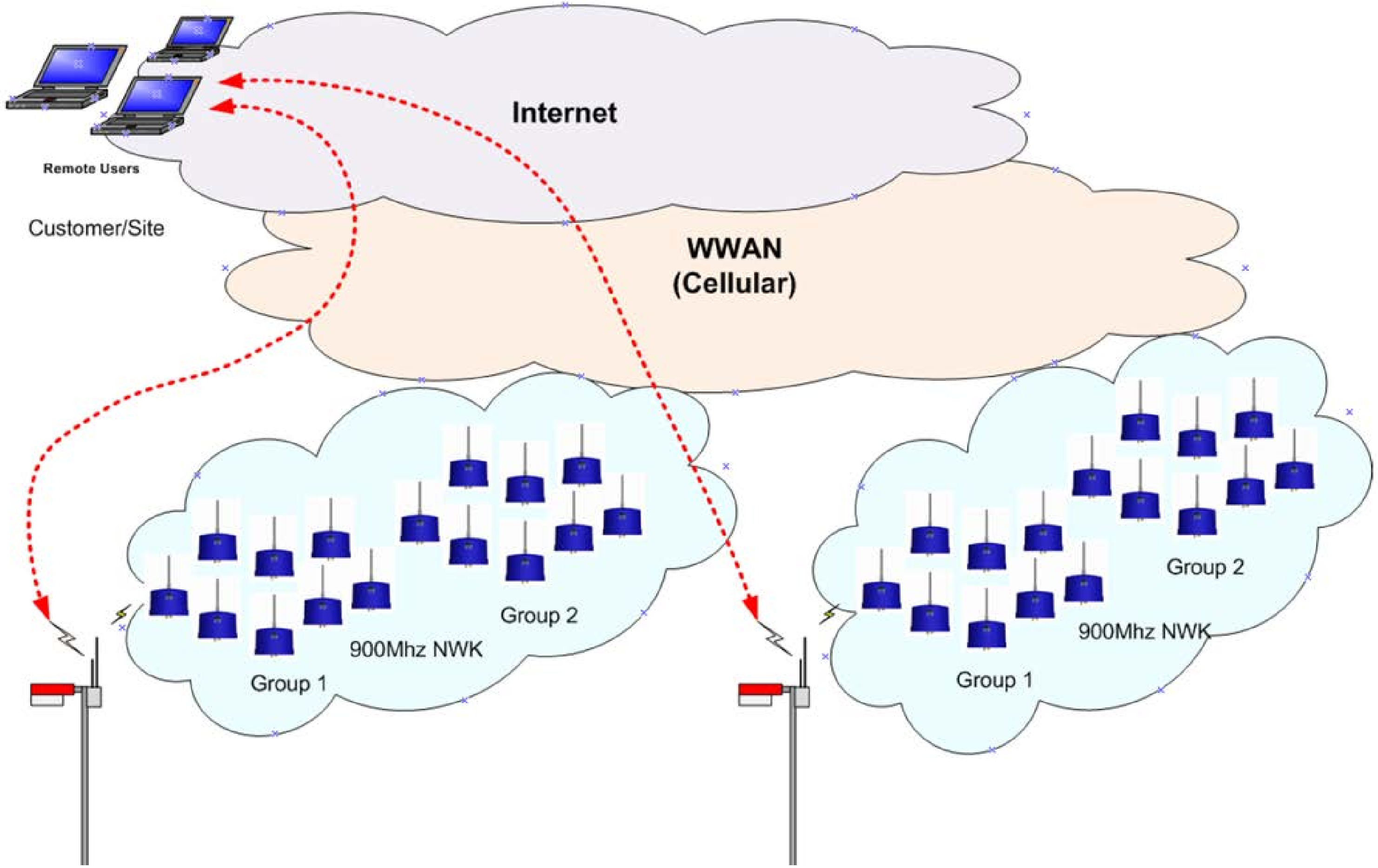
Here is what we know and don’t know

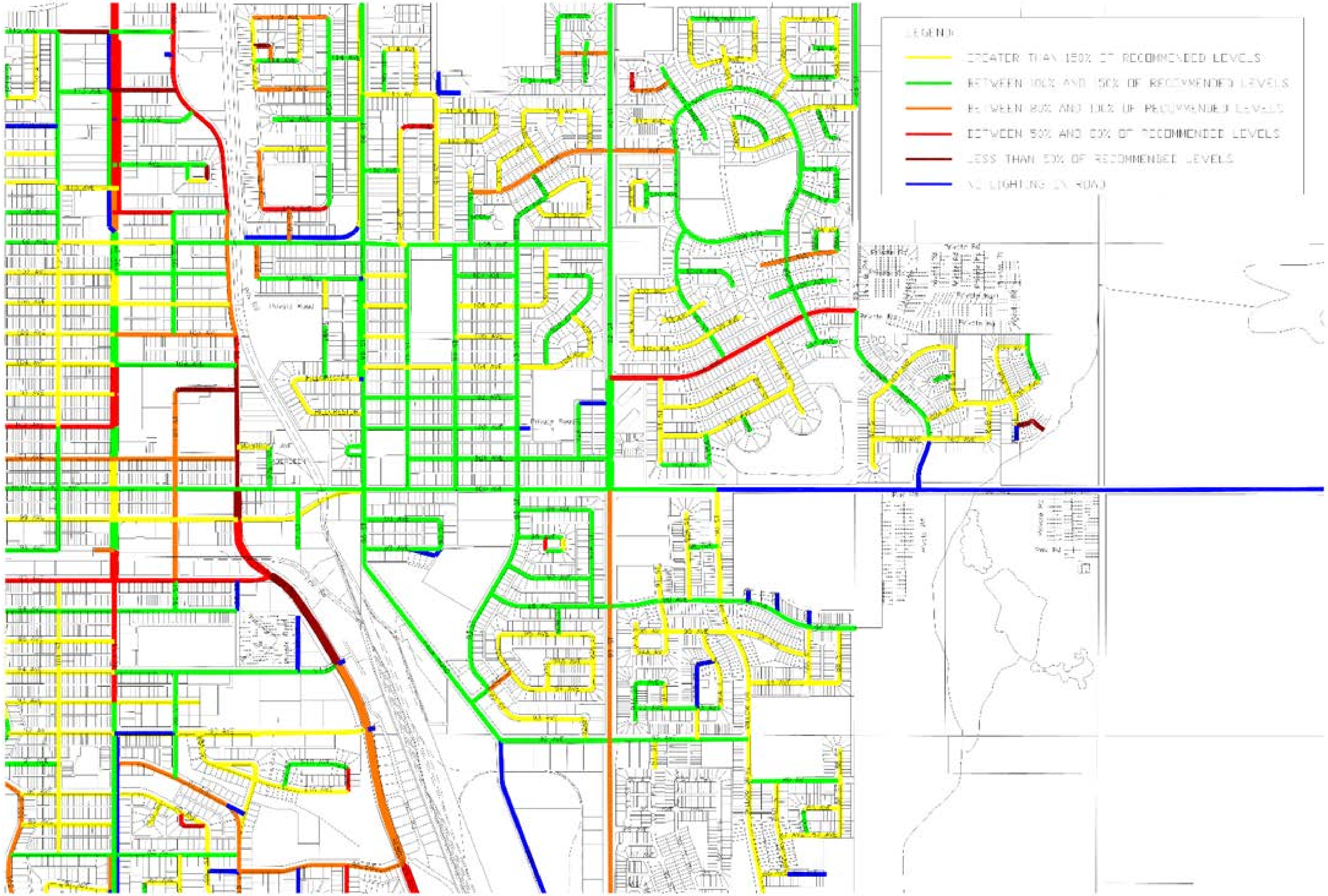
- Roadway lighting has an impact on safety.
- Spectral content impacts visibility.
- Roadway lighting seems to modify driver behavior.
- Many factors contribute to crashes with lighting and visibility being only one of them.

How Do We Currently Approach Design with All These Knowns and Unknowns?

Adaptive Lighting Example

Adaptive Lighting System




LEGEND:
GREATER THAN 150% OF RECOMMENDED LEVELS
BETWEEN 100% AND 150% OF RECOMMENDED LEVELS
BETWEEN 80% AND 100% OF RECOMMENDED LEVELS
BETWEEN 50% AND 80% OF RECOMMENDED LEVELS
LESS THAN 50% OF RECOMMENDED LEVELS
NO LIGHTING IN ROAD

Typical Street

IES RP-8 Recommendations

Roadway lighting levels	9 lux average 0.6 cd/m^2
Sidewalk lighting level	2 lux minimum vertical
Light trespass level (TM-11-00)	8 lux pre-curfew maximum 3 lux post-curfew maximum

Existing Condition

Roadway lighting levels	20 lux average 1.3 cd/m^2
Sidewalk lighting level	2.5 lux minimum vertical
Light trespass level	25 lux maximum
Power/unit	185 watts

Test Installation Condition Pre-curfew

Roadway lighting levels	12 lux average 0.8 cd/m^2
Sidewalk lighting level	3 lux minimum vertical
Light trespass level	6.9 lux maximum
Power/unit	86 watts

Table 3. Lighting Design Criteria for Streets

STREET CLASSIFICATION	PEDESTRIAN AREA CLASSIFICATION	AVG. LUMINANCE L_{avg} (cd/m^2)	AVG. UNIFORMITY RATIO L_{avg}/L_{min}	MAX. UNIFORMITY RATIO L_{max}/L_{min}	MAX. VEILING LUMINANCE RATIO LV_{max}/L_{avg}
MAJOR	HIGH	1.2	3.0	5.0	0.3
	MEDIUM	0.9	3.0	5.0	0.3
	LOW	0.6	3.5	6.0	0.3
COLLECTOR	HIGH	0.8	3.0	5.0	0.4
	MEDIUM	0.6	3.5	6.0	0.4
	LOW	0.4	4.0	8.0	0.4
LOCAL	HIGH	0.6	6.0	10.0	0.4
	MEDIUM	0.5	6.0	10.0	0.4
	LOW	0.3	6.0	10.0	0.4

L_{avg} - minimum maintained average pavement luminance
L_{min} - minimum pavement luminance
LV_{max} - maximum veiling luminance

Table 4 - Recommended Values for High Pedestrian Conflict Areas

Maintained Illuminance Values for Walkways			
	E_{avg} (lux/fc)	EV_{min} (lux/fc)	E_{avg}/E_{min}*
Mixed Vehicle and Pedestrian	20.0/2.0	10.0/1.0	4.0
Pedestrian Only	10.0/1.0	5.0/0.5	4.0

E_{avg} - minimum maintained average horizontal illuminance at pavement
E_{min} - minimum horizontal illuminance at pavement
EV_{min} - minimum vertical illuminance at 1.5m above pavement
*Horizontal only

Table 5 - Recommended Values for Medium Pedestrian Conflict Areas

Maintained Illuminance Values for Walkways			
	E_{avg} (lux/fc)	EV_{min} (lux/fc)	E_{avg}/E_{min}*
Pedestrian Areas	5.0/0.5	2.0/0.2	4.0

E_{avg} - minimum maintained average horizontal illuminance at pavement
E_{min} - minimum horizontal illuminance at pavement
EV_{min} - minimum vertical illuminance at 1.5m above pavement
*Horizontal only

Table 6: Recommended Values for Low Pedestrian Conflict Areas

Maintained Illuminance Values for Walkways			
	E_{avg} (lux/fc)	EV_{min} (lux/fc)	E_{avg}/E_{min}*
Rural/Semi-Rural Areas	2.0/0.2	0.6/0.06	10.0
Low Density Residential *(2 or fewer dwelling units per acre)*	3.0/0.3	0.8/0/08	6.0
Medium Density Residential *(2.1 to 6.0 dwelling units per acre)*	4.0/0.4	1.0/0.1	4.0

E_{avg} - minimum maintained average horizontal illuminance at pavement
E_{min} - minimum horizontal illuminance at pavement
EV_{min} - minimum vertical illuminance at 1.5m above pavement
*Horizontal only

TM-11-00

Light Trespass: Research, Results *and* Recommendations

IES
The LIGHTING AUTHORITY®

Publication of this Technical Memorandum has been approved by the IESNA. Suggestions for revisions should be directed to the IESNA.

Prepared by The Obtrusive Light Subcommittee of the IESNA Roadway Lighting Committee

Areas may be classified into a series of environmental zones, based upon the extent to which control of light trespass is considered necessary or desirable. These are described as zones E1, E2, E3, and E4, which are defined as follows:

E1. Areas with intrinsically dark landscapes. Examples are national parks, areas of outstanding natural beauty, or residential areas where inhabitants have expressed a strong desire for strict limitation of light trespass.

E2. Areas of low ambient brightness. These may be suburban and rural residential areas. Roadways may be lighted to typical residential standards.

E3. Areas of medium ambient brightness. These will generally be urban residential areas. Roadway lighting will normally be to traffic route standards.

E4. Areas of high ambient brightness. Normally this category will include dense urban areas with mixed residential and commercial use with a high level of nighttime activity.

Table 1. Recommended Light Trespass Limitations

Environmental Zone	Pre-Curfew Limitations*	Post-Curfew Limitations*
E1	1.0 (0.10)	0.0 (0.00)**
E2	3.0 (0.30)	1.0 (0.10)
E3	8.0 (0.80)	3.0 (0.30)
E4	15.0 (1.50)	6.0 (0.60)

* Lux (footcandles) values on a plane perpendicular to the line of sight to the luminaire (s).

**Where safety and security are issues, nighttime lighting is needed. Such lighting should meet IESNA recommendations for the particular property being lighted. Lighting should be designed, however, to minimize light trespass

Dimming Schedule

	Setback	Cleaning	Neighborhood	Street	Street ID	Pole No.	New Fixture	Notes	Quantity	Date	Installed By	Date Verified
463	10PM	H	9	Bolton Street	81-	22	A3		1	10/03/14	Dagle	10/28/14
464	10PM	H	9	Bolton Street	81-	23	A3		1	10/03/14	Dagle	10/28/14
465	10PM	K	9	Bond Street	83-	2	A2		1	06/26/14	Dagle	
466	10PM	K	9	Bond Street	83-	4	A2		1	06/26/14	Dagle	
467	10PM	K	9	Bond Street	83-	6	A2		1	06/26/14	Dagle	
468	10PM	K	9	Bond Street	83-	8	A2		1	06/26/14	Dagle	
469	10PM	K	9	Bond Street	83-	10	A2		1	08/22/14	Dagle	
470	10PM	E	7	Bow Street	84-	3	A2		1	10/06/14	Dagle	
471	10PM	E	7	Bow Street	84-	4	A2		1	10/06/14	Dagle	
472	10PM	E	7	Bow Street	84-	6	A2		1	10/06/14	Dagle	
473	10PM	E	7	Bow Street	84-	8	A2		1	10/06/14	Dagle	
474	10PM	E	7	Bow Street	84-	9	A2		1	10/06/14	Dagle	
475	10PM	H	9	Bowdoin Street	86-	1	A3		1	09/30/14	Dagle	
476	10PM	H	9	Bowdoin Street	86-	3	A3		1	08/25/14	Dagle	
477	10PM	H	9	Bowdoin Street	86-	5	A3		1	08/25/14	Dagle	
478	10PM	H	9	Bowdoin Street	86-	7	A3		1	08/25/14	Dagle	
479	10PM	H	9	Bowdoin Street	86-	10	A3		1	07/18/14	Dagle	
480	10PM	H	9	Bowdoin Street	86-	12	A3		1	08/25/14	Dagle	
481	10PM	H	9	Bowdoin Street	86-	14	A3		1	08/25/14	Dagle	
482	10PM	H	9	Bowdoin Street	86-	16	A3		1	08/25/14	Dagle	
483	10PM	K	10	Bradbury Street	90-	2	A3		1	06/27/14	Dagle	
484	10PM	K	10	Bradbury Street	90-	4	A3		1	06/27/14	Dagle	
485	Midnight	K	10	Brattle Street	92-	10	A2		1	08/22/14	Dagle	
486	Midnight	K	10	Brattle Street	92-	13	A2		1	08/22/14	Dagle	
487	Midnight	K	10	Brattle Street	92-	14	A2		1	08/22/14	Dagle	
488	Midnight	K	10	Brattle Street	92-	15	A2		1	08/22/14	Dagle	
489	Midnight	K	10	Brattle Street	92-	16	A2		1	08/20/14	CED	
490	Midnight	K	10	Brattle Street	92-	17	A2		1	08/20/14	CED	
491	Midnight	K	10	Brattle Street	92-	18	A2		1	08/22/14	Dagle	10/22/14

Responsive Design

- Ability to spectrally tune lighting for species/time of year
- Ability to dim the lighting system to lowest level which achieves the desired effect
- Run lighting effects or even static aesthetic lighting for limited periods each night
- Turn off system when expected to impact seasonal wildlife cycles like bird migration, turtle nesting, etc..

Questions?