Roadway Lighting: An Investigation and Evaluation of Three Different Light Sources

Final Report 522

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DISCLAIMER

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16. Abstract –

Nighttime visibility has been shown to be influenced by the lamp type used for roadway lighting, because the lamp's spectral output can influence sensors in the retina that are active at night. This report investigates the nature of these spectral effects and provides an in-depth review of available knowledge. It also addresses lighting levels and their relationship to driver safety. Three candidate lamp types have been analyzed in terms of technical characteristics and associated costs. This involves factors such as the efficacy with which the sources produce light, lamp life, and maintenance characteristics. Ideal lighting designs have been performed using the three sources for identical road sections, and initial and operating costs have been calculated, to assist in contrasting the difference between the sources. Two research plans have been developed for further investigations. One is a major project of field experimentation to determine relationships between visibility, safety, lighting level and lamp type under practical driving conditions. The other is based on using roadway sections lighted by the three sources respectively for the collection of accident data.

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SI (MODERN METRIC) CONVERSION FACTORS*

APPROXIMATE CONVERSIONS TO SI UNITS					APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol	Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH					**LENGTH**		
In	inches	25.4	millimeters	mm	mm	millimeters	0.039	inches	in
Ft	feet	0.305	meters	m	m	meters	3.28	feet	ft
Yd	yards	0.914	meters	m	m	meters	1.09	yards	yd
Mi	miles	1.61	kilometers	km	km	kilometers	0.621	miles	mi
		AREA					**AREA**		
in^2	square inches	645.2	square millimeters	mm^2	mm^2	Square millimeters	0.0016	square inches	in^2
ft^2	square feet	0.093	square meters	m^2	m^2	Square meters	10.764	square feet	ft^2
yd^2	square yards	0.836	square meters	m^2	m^2	Square meters	1.195	square yards	yd^2
Ac	acres	0.405	hectares	ha	ha	hectares	2.47	acres	ac
mi^2	square miles	2.59	square kilometers	km^2	km^2	Square kilometers	0.386	square miles	mi^2
		VOLUME					**VOLUME**		
fl oz	fluid ounces	29.57	milliliters	mL	mL	milliliters	0.034	fluid ounces	fl oz
Gal	gallons	3.785	liters	L	L	liters	0.264	gallons	gal
ft^3	cubic feet	0.028	cubic meters	m^3	m^3	Cubic meters	35.315	cubic feet	ft^3
yd^3	cubic yards	0.765	cubic meters	m^3	m^3	Cubic meters	1.308	cubic yards	yd^3
		NOTE: Volumes greater than 1000L shall be shown in m^3.							
		MASS					**MASS**		
Oz	ounces	28.35	grams	g	g	grams	0.035	ounces	oz
Lb	pounds	0.454	kilograms	kg	kg	kilograms	2.205	pounds	lb
T	short tons (2000lb)	0.907	megagrams (or “metric ton”)	mg (or “t”)	Mg	megagrams (or “metric ton”)	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)					**TEMPERATURE (exact)**		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C	°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION					**ILLUMINATION**		
Fc	foot candles	10.76	lux	lx	lx	lux	0.0929	foot-candles	fc
Fl	foot-Lamberts	3.426	candela/m^2	cd/m^2	cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS					**FORCE AND PRESSURE OR STRESS**		
Lbf	poundforce	4.45	newtons	N	N	newtons	0.225	poundforce	lbf
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa	kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

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ACRONYMS	
AASHTO	American Association of State Highway and Transportation Officials
ANSI	American National Standards Institute
CIE	Commission Internationale de l'Eclairage (International Illumination Commission)
CRI	Color Rendering Index
EPRI	Electric Power Research Institute
FHWA	Federal Highway Administration
GE	General Electric Company
HFC	Horizontal Footcandles
HPS	High Pressure Sodium
IES, IESNA	Illuminating Engineering Society of North America
ITE	Institute of Transportation Engineers
KCPL	Kansas City Power and Light
LEM	Lumen Effectiveness Multiplier
LPS	Low Pressure Sodium
LRC	Lighting Research Center (Rensselaer Polytechnic Institute)
MH	Metal Halide
MUTCD	Manual on Uniform Traffic Control Devices
R3	Reflectance classification for a blacktop pavement with medium wear.
SCF	Spectral Correction Factor
SPD	Spectral Power Distribution
STV	Small Target Visibility
VFC	Vertical Footcandles

TERMINOLOGY

Adaptation	The process by which the eye adjusts to different luminance levels.
Candelas/sq.m.	The unit of luminance (SI).
Candlepower	US term for intensity, or luminous intensity. Refers to the concentration of light in a particular direction. Unit: candela. (cd)
Color Rendition	The ability of a light source to produce object colors truly.
Cones	Sensors in the retina that reduce their input as light level falls; have peak sensitivity to yellow light with low sensitivity to blue-green light.
Dirt Depreciation	The reduction in luminaire lumen output due to dirt accumulation.
Efficacy	The ratio of initial lamp lumen output to watts input to lamp. Lumens per watt.
Footcandle	The unit of illuminance (English.) Metric unit is the lux 1 fc = 10.76 lux.
Fovea	Central portion of the eye's field of view, corresponding to on-axis vision. This area of the retina is densely packed with cones for discrimination of detail.
Foveal field	The field of view seen by the fovea.
Glare	Visual effect produced by an area in the field of view that has substantially higher luminance than that to which the eye is adapted. May be discomfort glare (a feeling of pain or unease) or disability glare (a luminous veil that reduces the contrast of objects and visibility).
Illuminance	The density of light falling on a surface. Measured in footcandles. 1 footcandle = 1 lumen per sq. ft.
Illuminance Method	A design methodology based on specified levels and uniformities of illuminance.
Initial Lamp Lumens	Lamp lumen output after operating for 100 hours.
Intensity	See candlepower.
Lamp Cycling	The repeated switching on and off exhibited by some lamps when end of life has been reached.
Lighting Level	May be either illuminance (light density falling on a surface such as a roadway), or luminance (light density reflected from a surface.)
Lumen Depreciation	The reduction in lamp lumen output over lamp life.
Lumen Maintenance	See Lumen Depreciation.
Lumen	The unit of light power

Luminance	The reflected light level, sometimes referred to as brightness (although not strictly correct). Measured in candelas /sq.m. Luminance influences the operating state of the eye in terms of the relative input from the rod and cone systems of the retina.
Luminance Method	A design methodology based on specified levels and uniformities of pavement luminance.
Mean Lamp Lumens	Average lamp lumens over the lamp's rated life.
Mesopic	Light level conditions characterized by the state of adaption of the retina; typically luminances between 0.001 and 3 cd/sq.m. where both the rods and cones are active.
Monochromatic Source	A lamp having all, or substantially all, of its light output at a particular wavelength, or narrow wavelength range.
Nanometer	Unit of wavelength. (10^{-9} meter)
Non-monochromatic Source	These lamp types usually produce light over the entire visible spectrum.
Off-axis Vision	Vision outside ± 1 degree of the direct line of sight.
On-axis Vision	Vision within ± 1 degree of the direct line of sight.
Peripheral Vision	See off-axis vision.
Photo Control	A photoelectric cell used to switch luminaires on and off at dusk and dawn respectively.
Photopic	Light level conditions characterized by the state of adaption of the retina; typically luminances above 3 cd/sq.m. where the cones are primarily active.
Pulse Start	A form of starting and operating a lamp using a high voltage ignitor coupled to the ballast. HPS and modern MH lamps are pulse start.
Rated Lamp Life	The number of burning hours at which 50% of lamps of the given type are likely to have failed.
Rated Lumens	Lumens as assigned by a manufacturer, describing the typical light power output of a particular lamp.
Reflectance	A measure of the extent to which a surface such as a pavement reflects light. Determines the surface luminance for a given illuminance.
Rods	Sensors in the retina that become active at low light levels; situated outside of the central line of sight; have peak sensitivity to blue-green light with low sensitivity to yellow light.
Scotopic	Light level conditions characterized by the state of adaption of the retina; typically luminances less than 0.001 cd/sq.m. where only the rods are active.
Small Target Visibility, STV	A method developed by IESNA to determine the visibility of small targets placed in an array on a roadway surface.

Spectral (Power) Distribution (SPD)	The variation in power output across the visual spectrum from a light source.
System Wattage	The sum of lamp input power and power losses in the ballast. Identical to luminaire wattage. May also be applied to a complete installation of luminaires.
Threshold Increment	A measure of disability glare. Not used in USA.
Utilization Factor	The ratio of lumens from a lamp falling on the surface to be lighted, such as a roadway, to the bare lamp lumens.
Visibility	May be measured in terms of visual acuity (ability to see small details), contrast sensitivity (ability to distinguish between areas of differing luminances), reaction time (time to react after a visual stimulus), or other measures.
V-lambda Curve, $V(\lambda)$	The graph of sensitivity of the cones of the retina versus light wavelength.
V-lambda Prime Curve, $V'(\lambda)$	The graph of sensitivity of the rods of the retina versus light wavelength.

1. INTRODUCTION

Roadway lighting is an important part of a highway system. It contributes to a safe environment and facilitates traffic flow for the traveling public during evening or nighttime driving. There is a growing concern to identify in Arizona, as in many other states, the impact of roadway lighting practices on the surrounding environment, as well as the significance of the key issues of energy efficiency and cost. Light trespass and light pollution from roadway facilities and other outdoor lighting systems have become significant local concerns, and many Arizona communities have adopted lighting ordinances that vary, to some extent, in their emphasis, clarity, and detail, with the intended purpose of reducing such problems. The deployment of roadway lighting systems that meet the safety needs of the motoring public in a cost-efficient manner, without adversely impacting the surrounding environment, is a basic goal of the Arizona Department of Transportation (ADOT).

The research described in this report reviewed certain aspects of the subject to determine whether it is possible and desirable to improve lighting design practices. Given the known relationship between roadway lighting and safety, improvements in such lighting may be expected to decrease accidents. Conventional thinking regarding lighting has been that increased illumination levels provide a better seeing environment and those light sources which produce the most lumens per watt are the most effective in providing this illumination. However, as a result of recent research, consideration is being given to changing or refining the Commission Internationale de L'Eclairage (CIE) standard observer response (also known as the photopic luminous efficiency function) that favors the yellow light definition of the lumen. It is this curve that has been the key to all photometry which defines the "useful" lumen. Refinement or change to this curve could represent a significant change to how useful light is defined and how lighting systems are designed; how each light source is evaluated regarding its effectiveness could change. This could significantly alter what light sources are used and what lighting levels are specified. These considerations of change and/or refinements have led to much controversy and discussion within the lighting industry. This research project was undertaken to determine the status of the subject and to find what can be done or needs to be done to better define the issues. In this way, the feasibility of potential benefits might be better assessed. The importance of this work is widely recognized. Both IESNA and CIE have established committees to review available knowledge of the subject and develop related technical publications.

High pressure sodium (HPS) lights are the most commonly used type of roadway lighting. They have the inherent advantages of long life, (hence less maintenance), low cost, energy efficiency and good long range optical control. Two other light sources, however, are also used to provide roadway lighting: low pressure sodium (LPS) and metal halide (MH). All of these sources are energy efficient. Newer sources such as inductive fluorescent, compact fluorescent and light emitting diodes may be practical sources in the future.

The Arizona Department of Transportation is interested in obtaining information on the three sources as related to visibility and safety, lamp performance, and accidents. This will help ADOT determine whether its standard HPS lighting design policy, with substitution of LPS or MH on a local-request case-by-case basis, should continue, or whether the body of recent research into roadway lighting safety and efficiency may justify changes in this lighting design policy. Each source has advantages and disadvantages. A study of these is needed to develop an understanding of the applicability of each source under differing roadway conditions and local regulations.

There are many aspects of roadway lighting design: sufficient light for the driving task, color rendition, glare, eye fatigue, lighting sources, and light pole spacing, to name a few. The main objectives of roadway lighting, however, are to help provide a safe environment for the motoring public and to facilitate traffic flow. A basic goal of good roadway lighting design is lighting that illuminates the roadway effectively with low maintenance requirements and high levels of traveler safety, while producing minimum light pollution or trespass. Fundamental, relevant questions that bear on any decisions in regard to ADOT's current roadway lighting practice are:

- Do different lamp color (or spectral power distribution) characteristics affect visibility and safety in a real roadway environment in a way that has a meaningful or measurable effect on driver performance?

- If a different choice in light source spectral distribution from that most commonly used now does result in potential driver performance improvement, what would be the tangible benefits be: reductions in crashes, light pollution, energy use? What would the drawbacks be: increased light pollution, more maintenance, higher initial costs?

- Certain local regulations require the use of a specific lamp type, which has raised controversy. Can ADOT conform to regulations requiring the use of a particular lamp type while meeting desired goals?

- Can and should ADOT make a change from its current designs to light sources with different color rendering characteristics, such as metal halide, or low pressure sodium?

- Can and should ADOT recommend changes to standards writing bodies from their current design standards to lower lighting levels, or to higher lighting levels?

- What maintenance issues are involved in changing lamp type?

- Does the current state of research justify an immediate change to lighting design practice or is more research needed to see if the current results are in fact meaningful?

- What will this research cost?

In October 2001, ADOT issued a Request for Proposal (RFP) detailing the desired studies. The RFP was divided into two subject topics, covering two separate but conceptually related general areas, as described below. Lighting Sciences, Inc., of Scottsdale, Arizona, was the successful bidder, and the work effort commenced in June 2002.

The project was organized to include two phases of work on each of the two topics, with a decision point after the first phase. The initial research phase, decision support, was intended to inform ADOT on the state of the practice, current lighting theory, and safety issues. The goal was to determine whether new research on either topic would be justified, practical, and timely. The second phase was to develop detailed scopes of work for more expansive future research efforts that could resolve the issues being defined in the project.

The objectives of Topic One of the research project have been to investigate spectral distribution and lighting levels, specifically:

- To evaluate the benefits to the Department of a future research program which would investigate the potential impact on motorist driving performance of different light source spectral distribution and roadway lighting levels.

- To recommend if and when the Department should initiate such work, and if so,

- To develop a proposed plan of research to study the impacts of changes in the roadway lighting levels and lighting sources.

Possible benefits of such changes are:

- Potential improvements in driver performance because drivers may be able to see better or just as well at a lower light level.

- Potential to provide roadway lighting systems at a lower per mile energy cost.

- Increased driver comfort resulting from improved visibility, possibly resulting in better capacity and traffic flow.

- Improved chromatic contrast which allows colors to be seen better, thus assisting in object identification.

- Improved general appeal of nighttime activity, an important issue if an area experiences high nighttime use.

These benefits will not be immediately recognized as a result of the research program. Standards development, even when based on sound research, is a lengthy procedure. Early commencement of such a research program will advance the point at which potential benefits may accrue.

The objectives of Topic Two of this research project have been to perform in-service safety evaluation of lamp types, specifically:

- To provide a detailed comparison of the in-service performance, maintenance requirements, life-cycle costs, and crash experience for high speed roadway applications using LPS, HPS, and MH.
- To develop tabular summaries and reports of a typical roadway segment with each light source design, providing side-by-side comparisons of the three lighting system designs.
- To develop a proposed plan of research to evaluate crash experience on similar roadways lighted by the three different sources.

Sections 2 and 3 of this report provide brief summaries of the topics. Appendixes A through D provide the detailed reports.

The work on both topics has included several meetings with the Technical Advisory Committee (TAC), which consisted of the following persons:

Robert Alcala	Alcala & Associates
Kenneth Cooper	Arizona Department of Transportation Intermodal Transportation Division
Don Dorman, John Harper Chuck Gillick	Arizona Department of Transportation Flagstaff District
Ray Johnson	Arizona Department of Transportation Traffic Engineering
Christian Luginbuhl	United States Naval Observatory
Gerald Craig	City of Flagstaff
Matt Ryan (Linda Locke - alternate)	Coconino County
Seth Chalmers	Chalmers Engineering
Frank McCullagh Steve Owen	Arizona Transportation Research Center
Jennifer Brown Alan Hansen	Federal Highway Association

The TAC has guided the consultants in developing the material presented in the Appendixes so that it meets the requirements of the RFP.

The work effort for Topic One has achieved all of the stated objectives. A substantial amount of information was found relating lamp color to visibility. However, the extent to which the information may relate to roadway safety has not been ascertained. The TAC therefore authorized the consultants to develop a research plan to investigate the effects further.

Topic Two work efforts succeeded in obtaining responses from a large number of agencies. All but two state DOT's responded to the consultant's questionnaire. None reported any data relating lamp type to crash experience. This resulted from the very limited usage of low pressure sodium and metal halide sources, and also was because data are not normally collected that relate light source type to crash statistics. This emphasizes the need for further research to allow the collection of such data, and the consultants were requested by the TAC to develop a program of research to collect relevant field data.

Section 4 of this report, Results and Recommendations, provides a summary of the finding of the work.

The schedule anticipated completion of the work by the end of December 2002. Actual performance took 4 months longer than expected.

2. TOPIC ONE – SPECTRAL DISTRIBUTION AND LIGHTING LEVELS

2.1 INTRODUCTION

The specific objectives of Topic One of the research project have been:

- To evaluate whether a future research program, which would investigate the potential improved driver performance as related to light source spectral distribution and roadway lighting levels, would provide benefits to the Department.

- To recommend if and when ADOT should initiate such work. If so, then to develop a formal plan of research to study the impacts of changes in the roadway lighting levels and lighting sources on safety and other benefits.

The Topic One work stages were:

- A preliminary meeting was held with the TAC to initiate this research project. Subsequent meetings occurred at points during the project. Monthly progress reports to the TAC have been provided.

- A review was done of the literature on the effect of light source spectral distribution and color rendition on visibility and roadway lighting levels. A technical memorandum has been prepared that reviews available information on the subjects involved (see Appendix A). A formal recommendation has been made with respect to the Department's goals and objectives to meet safety needs in a cost-efficient manner, in relation to current ADOT lighting practice. This includes a technical memorandum describing the relative benefits, timeliness, and efficacy of a possible decision by the Department to initiate research in this area at this time.

- Following discussion of the technical report by the TAC, the consultants were authorized to proceed with the development of a research plan to further investigate the topic. Appendix C provides the research plan, and includes problem statements, research objectives, research tasks, expected implementation, funding requirements, potential research partnerships, and program duration.

A bibliography and copies of all of the reports used in the review have been separately provided to ADOT.

2.2 TECHNICAL OVERVIEW

Lamp lumens are the product of the emitted energy over the visible wavelength range, factored by the eye sensitivity curve, or the eye's spectral response. It has been recognized since the mid-1800's that the human eye undergoes a spectral sensitivity

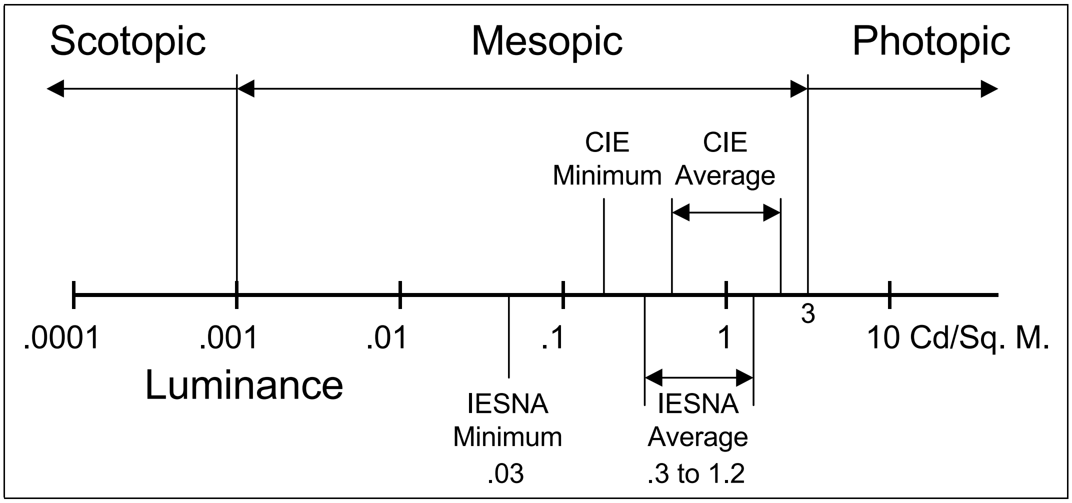

Figure 1. The range of photopic, mesopic and scotopic light levels.

shift between high and low light level conditions.(1) At high light levels, over approximately 3 candelas per square meter (cd/m^2), the dominant receptors in the retina are the "cones." The cones have peak sensitivity to yellow light. Such levels are referred to as "photopic." As lighting levels are reduced below 3 cd/m^2, the cones become less and less active, and the "rods" of the retina become active and assume increasing importance in providing visibility. The rods have a peak sensitivity to blue-green light. At extremely low light levels as may be found with starlight, only the rods are active. These levels are referred to as "scotopic." Roadway lighting levels are almost invariably in the range of 0.1 to 2.0 cd/m^2, and are in the "mesopic" range of vision where both rods and cones are active. These ranges and the roadway lighting levels recommended by CIE and IESNA are illustrated by Figure 1. Figure 2 shows the response sensitivity curves of the cones and rods respectively. Mesopic response is a complex mix of the photopic and scotopic responses.

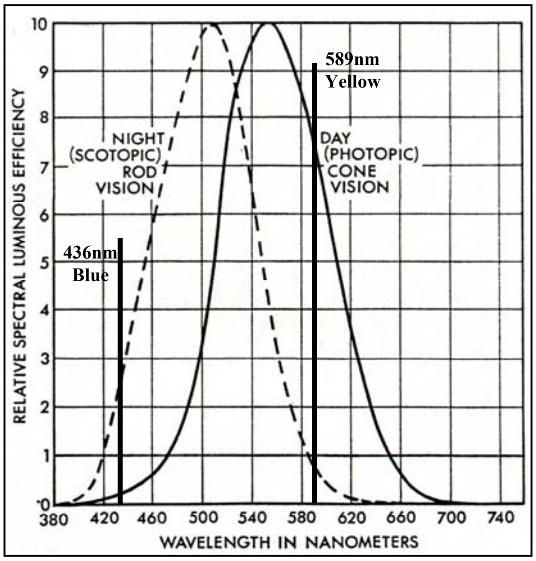

Figure 2. The V(λ) curve for photopic vision and the curve for scotopic vision.

Lamp lumens values as published by manufacturers and used by lighting designers are based purely on the spectral response of the cones of the eye. Thus they are determined for high light level conditions. Sodium sources have high lumens per watt because the peak sensitivity of the cones is in the yellow region, where these sources release most of their energy. White light sources such as metal halide produce all wavelengths of light, including a high proportion of blue and green energy. Because the proportion of light produced in the yellow region is less than sodium sources, metal halide sources have lower lumens per watt.

If light sources were to be evaluated in terms of the visibility produced by the rods of the retina, which are active at low light levels and which show peak sensitivity in the blue-green range, the advantage of sodium sources would be lost. The yellow emission would be no longer associated with the eye's peak sensitivity, because rod response is maximum in the blue-green region. It is then the white source, with its proportionally higher blue-green output, that would stimulate the peak sensitivity of the rods.

Under mesopic conditions, where both rods and cones are active, the response characteristics of both sensors become important. Visibility is linked to how each of the two retinal systems responds to the particular waveform of the lamps used.

The visibility created by a particular source is related to the lighting level, all other factors being equal, and in general, visibility decreases as the light level decreases. However, as the light level decreases, the rod system becomes more active and factors related to rod response assume greater importance. A key question is to what extent rod response provides significant visibility of roadway hazards at practical roadway lighting levels.

The matter is further complicated by the fact that the distribution of cones and rods is not uniform throughout the retina. Only cones lie at the exact center of the field of view, while rods are significant in the peripheral field. The location of the visual task, or object to be seen, therefore affects visibility in a complex manner, which again is affected by the lamp spectral distribution.

Dr. Alan Lewis, President of the New England School of Optometry, has conducted laboratory studies that investigated light level, sensitivity to contrast, and reaction time for several light source types: mercury, metal halide, incandescent, high pressure sodium and low pressure sodium.[2,3] An example set of results is provided in Figure 3. In this experiment, observers were asked to detect the appearance of a person standing at the curb and to determine whether the person constituted a possible hazard (pedestrian facing the roadway) or not (facing away). Figure 3 graphs the time taken by the observers to make this determination versus luminance level, for the various sources. At moderately high lighting levels of 3 cd/sq.m. and over, light source type has no effect. As lighting levels become progressively lower however, the sodium sources require increasingly longer reaction times versus the white MH source. At very low levels, the difference is very significant.

Figure 3 illustrates also that a given visibility, as measured in terms of reaction time, is achievable using all three sources, at least over a limited range. The horizontal line representing 775 msec reaction time intersects all three curves. Dropping vertical lines from each curve to the X-axis provides the luminance level needed to produce that reaction time in this experiment for each source. This visibility can be produced by a much lower level of MH than HPS. For LPS, a higher lighting level is needed to produce the illustrated reaction time.

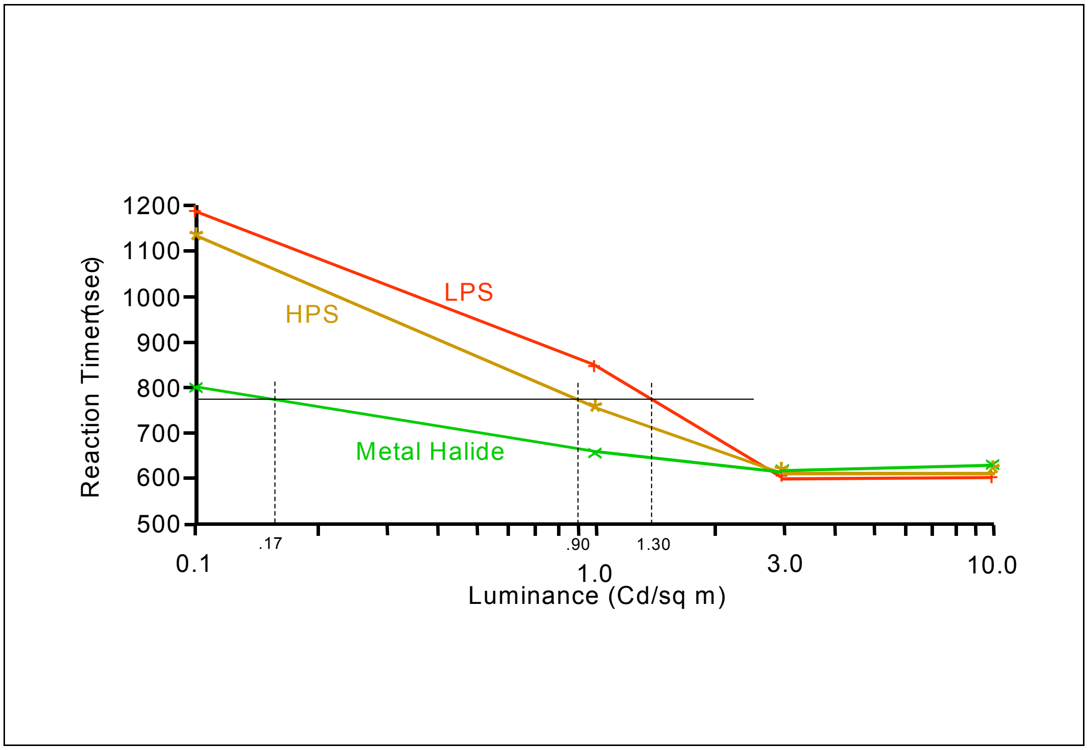

Figure 3. Data from Lewis Research

Thus a trade-off can be seen to exist between lighting level, visibility and lamp type. To the extent that data similar to those shown in Figure 3 are applicable in the real-world situation, it appears that use of MH sources could allow a reduction in lighting levels. Conversely, if LPS is used to provide similar lighting levels as are typically designed today, evidence suggests that roadway visual tasks that are affected by mesopic vision characteristics will have reduced visibility, and that a decrease in safety is a possible result.

However, many factors are involved in determining the extent to which such visibility characteristics apply in real world situations. The nature of the driver's visual task can strongly influence such effects.

Professor Werner Adrian of the University of Waterloo, Canada, has performed calculations of the expected effects of light source type at low light levels, based on data gathered by the CIE (Commission Internationale de l'Eclairage, or the International Illumination Commission).[4] Adrian's data show similar trends to those of Lewis.

Professor Mark Rea and his associates at Rensselaer Polytechnic Institute have performed extensive studies of this subject using laboratory testing and driving simulators.[5-9] They too produced results that suggest that certain types of accidents are likely to be reduced by the use of white light as opposed to yellow. However, other forms of visual tasks, those at very high light levels or directly in the line of sight, were found not to be affected by lamp type.

Thus the issues can be seen to be complex. Numerous factors must be considered and analyzed, which is difficult because of incomplete information on some of the effects involved. The current state of knowledge of the subject has been analyzed in-depth as the primary work effort under Topic One of this project. Recognizing that further research is needed, a plan of research was developed; see next section for additional information.

Color rendition also requires consideration. Certain objects are color coded by federal regulation and it is desirable to have similar nighttime and daytime color appearance. Most notably these are roadway markings, typically white and yellow, and signage. Use of a monochromatic source such as LPS, or a spectrally deficient source such as HPS, will yield a change in color rendition at night versus daytime.

The extent or impact of color rendering within the context of roadway lighting is not well understood. This subject is complicated due to the fact that pavement markings and signs are typically made of reflective materials (glass beads and prismatics) that greatly enhance their ability to reflect light back to its source. (This process is called retroreflection). Thus, the pavement markings and signs which are in line with the vehicle headlamps are primarily illuminated by the vehicle headlamp light, not the roadway lighting. Under conditions like these the color of these objects are rendered under a combination of headlamp light (which typically has excellent color rendering potential) and roadway lighting sources. The power and extent of that rendering depends on the location of the object. If it is close to the vehicle within the coverage of high intensity from the headlamps the retroreflective color rendering will more than likely overpower the rendering or distortion caused by the roadway lighting system. However, outside the high intensity areas of the headlamps the color rendering will be much more dependent on what is provided by the roadway lighting system.

An in-depth review of the many visibility factors involved in lamp selection is provided in Appendix A.

2.3 RESEARCH PLAN

The research plan developed as part of the Topic One work effort has as its broad objective the development of data relating lighting source type, lighting level, visibility and safety. This commences with the listing of safety-related driver tasks that can be influenced by the lighting system.

- Field testing of driver capabilities regarding such visual tasks that are performed by a driver, under controlled conditions, for differing lighting levels and lamp types.

- Investigation of related effects of oncoming headlight glare and variable weather conditions.

- Consideration of reflected light from the pavement and other surfaces, as it may be related to light pollution.

- Development of a set of recommendations relating all of these factors for possible inclusion into ADOT lighting practice.

The research plan has a detailed list of studies to be done on driver visual tasks and lighting system specifications. It discussed the acquisition of a test facility and luminaires, and the methods to be used to evaluate the luminaires. Driver response, experimental design and recruitment of test subjects has been discussed. Performance of the experiments and the variables to be evaluated are described.

It is proposed in the plan that the research be conducted in a closed test facility, specially built or modified for the purpose.

An estimate of required funding has been made, not including the test facility, of roughly $700,000.

The research plan provides a breakdown of the overall plan into three separate stages, should funding restraints lead to a phased research program. The three-stage approach is expected to increase the overall cost by approximately seven percent.

A period of performance of roughly two and a half years is anticipated, after the facility becomes available, for the project to proceed.

3. TOPIC TWO – IN-SERVICE SAFETY EVALUATION OF LAMP TYPES

3.1 INTRODUCTION

Topic Two of this research project provides a detailed comparison of the in-service performance, maintenance requirements, life-cycle costs, and crash experience of LPS, HPS, and MH in high-speed roadway applications.

This analysis has developed tabular summaries and textual reports of a typical roadway segment with each light source design. These provide side-by-side comparisons of the three lighting system designs.

The Topic Two work commenced with discussion of the subject with the Department's TAC at the preliminary meeting and subsequent meetings.

A detailed literature search and state-of-the-practice review of the subject of roadway lighting sources has been conducted. This review included contacting all of the state Departments of Transportation as well as relevant local municipal agencies. The review included a selection of European, Australian and other international agency sources.

Technical documentation with regard to light sources from the following agencies was studied:

- Federal Highway Administration (FHWA)
- American Association of State Highway and Transportation Officials (AASHTO)
- Institute of Transportation Engineers (ITE)
- Illuminating Engineering Society of North America (IESNA)
- Electric Power Research Institute (EPRI)
- Commission Internationale de l'Eclairage (CIE)

From the available literature, agency contacts, existing lighting system data and other sources, information was collected with regard to present light source usage, and requests were made for any related crash experience.

From available literature, primarily from CIE and IESNA, information was collected regarding lighting practice, including lighting levels, as related to accidents.

Side-by-side example installations have been studied. This included the development of a hypothetical roadway design for side-by-side comparisons of the three roadway lighting designs, based on a section of rural highway as specified by the TAC. This example quantifies the components of each system for a given length of roadway and effectively illustrates the comparison of all of the in-service and life-cycle information for the three light source systems.

A technical memorandum has been presented to the TAC giving detailed results of the research comparing the in-service performance of the three light sources. (See Appendix B.) A bibliography and copies of all of the reports used in the review have been provided.

Following discussion of the technical report by the TAC, the consultants were authorized to develop a formal plan of research to compare the three lighting sources in a future side-by-side field study. The plan has been developed: it includes problem statements, research objectives, research tasks, expected implementation, funding and site requirements, potential research partnerships, and program duration. The research plan is included as Appendix D.

3.2 TECHNICAL OVERVIEW

The purpose of the research conducted as part of Topic Two was to compare the three sources in terms of their technical features and costs associated with their in-service use. A further purpose was to collect accident data from agencies, both national and international, to determine whether such data indicate any relationship between safety and lamp type.

Low pressure sodium lighting is of interest for two main reasons. Firstly, it produces the highest lumen output per watt of any light source. Secondly, because it is monochromatic, its wavelength can be filtered out by astronomers, effectively removing any light pollution it causes. As a result, it is specified in several Arizona lighting codes, (including those of the City of Flagstaff and Coconino County).

Low pressure sodium, however, is more expensive than HPS or MH. LPS is also physically large, which increases fixture cost. Cost is also increased because of the low volume of fixtures produced. In addition, because of its monochromatic yellow color, objects lighted by LPS alone are not seen as having any color other than yellow. LPS has excellent characteristics in terms of lumen maintenance; it retains close to its original light output throughout its life. Because LPS lamps are large, precise optical control of their output is not possible using a fixture of a practical size. They are useful for providing wide general illumination, but where light must be thrown from a considerable distance, and/or used to light a narrow roadway they are at a disadvantage to HPS and MH. Low pressure sodium fixtures typically must be spaced more closely together than those using either of the other two lamp types. This increases costs, offsetting the lower energy cost created by their high lumens per watt. A closer spacing of poles also constitutes an increased number of obstacles for the driver, and may constitute a safety hazard in run-off-road crashes.

Metal halide, a white light source, has been shown in laboratory studies to produce greater visibility for certain driving tasks than sodium sources. However, there are disadvantages to this lamp type also. Its life is not so long as HPS, necessitating more frequent lamp replacement. Its lumen output per watt is high but not so high as HPS or LPS, and its lumen depreciation over life is the worst of the three sources. It is of a size similar to HPS, therefore MH fixtures are of comparable and reasonable cost. Being small, its output can be accurately controlled and wide pole spacings are usually possible.

The color characteristics of metal halide are excellent, thus providing the best color rendition of the three sources. This may be important when considering the color of road signs, although the full value of this color rendition benefit is uncertain, particularly in the presence of headlights.

Metal halide technology is rapidly evolving, and field data based on lamps placed into service over two years ago is largely obsolete. The new lamp types have increased life, higher lumen output and better lumen maintenance than their predecessors, although they are still not as good in these respects as the sodium sources. Very recent improvements by the use of electronic ballasts have decreased lumen depreciation over life.

The report provided as Appendix B gives in-service data for the three lamp types, thus taking into account their lumen depreciation and maintenance characteristics. Initial lumens, as emphasized by lamp manufacturers, are not considered particularly relevant. Lamp and fixture costs are addressed.

Part of the work has been the development of three lighting designs, one for each lamp type, for identical applications. Optimization was conducted using computerized lighting system design to determine the widest pole spacings for each lamp type that would meet the same lighting specifications. Capital costs were found to be the highest for LPS, primarily because of the need for reduced pole spacings. Capital costs for MH were slightly higher than for HPS. Energy costs were lowest for LPS and roughly equal for MH and LPS. Maintenance costs were found to be highest for LPS and lowest for HPS. Overall operating and owning costs over a 30 year system life were highest for LPS, and slightly higher for MH versus HPS.

Appendix B, the Topic Two summary report, summarizes the results obtained from questionnaires sent out to all states and certain other authorities. The questionnaire sought to identify the type of light source used in the various jurisdictions. It also requested accident data related to the lamp type in use.

Excellent response to the questionnaire was obtained. However, very few respondents indicated the use of any source other than HPS. Unfortunately, no agency was able to present any data relating accidents or operating costs to lamp type. Recognizing that such data would be very valuable, a research plan was developed for the collection of the same.

3.3 RESEARCH PLAN

The research plan developed as part of the Topic Two plans the collection of accident data to determine whether a relationship to lamp type can be demonstrated. This is to be achieved using existing roadways, with three near-identical sections lighted respectively by the three sources. It has been estimated that the three sections should not be less than 5 miles each in length, with the length being governed by several factors, including accident frequency.

Specific work tasks that have been developed are:

- Site selection.
- Facility implementation: design and installation of the lighting system.
- Accident data collection
- Report development

The data collected would relate number of accidents, severity, type, and relevance to peripheral vision elements.

It is proposed to use existing roadways, with the three lighting systems designed to produce identical lighting conditions, as far as is practical, apart from lamp type.

Estimated costs for the research project are approximately $75,000. This does not include the cost of providing the infrastructure with the three lamp types.

To develop an adequate database of accident records from the proposed test corridor for analysis, the duration of this study is anticipated to be at least three years.

4. RESULTS AND RECOMMENDATIONS

4.1 SPECTRAL DISTRIBUTION AND LIGHT LEVEL

The Topic One work effort has been successful in achieving the objectives of the program.

A wealth of published information has been found on the subjects of lamp color, lighting level and visibility. Numerous references are provided in appendixes A and B. The influence of lamp color on visibility, and therefore presumably on safety also, can be important. Certain experiments have indicated that driver response may be considerably improved when the lamp spectrum is attuned to stimulation of the rods, that is, when white light is used. However, other experiments indicate no difference in visual performance between the light source types. In general, experiments where peripheral vision is a significant visual input show benefits of MH sources. Where vision is achieved primarily by the fovea, or the direct line of sight, the lamp types are equal.

The research therefore has led to the conclusion that the extent to which MH can improve vision, or to which LPS can reduce visibility reduction (versus HPS), is dependent upon the relative importance of peripheral and foveal vision for the driver.

Knowledge on this point is incomplete. While it is generally recognized that both foveal and peripheral vision are important, the literature search and analysis have indicated that we do not have a good understanding of the nature of the driver visual tasks that are related to accident causes and prevention.

This is a critical point. If driver visual tasks that influence accidents are foveal, use of MH sources is unnecessary, and use of sodium sources can be beneficial, all other factors being equal. If such tasks are primarily peripheral, MH usage can increase visibility versus sodium sources. Lack of such information has led the consultants to recommend further research. The interrelationship between lamp spectrum, visibility and safety requires field evaluation under conditions representative of normal driving. When more information on the above problems is available, ADOT will be better positioned to decide whether to alter current roadway lighting practice.

The consultants feel that a closed facility is needed for this research work, to achieve controlled experimental conditions and avoid any issues of road user liability.

Investigations on the related subject of lighting level versus visibility and safety also have been inconclusive. While national and international standards exist, these are found to be based on consensus rather than controlled research. There is much evidence that lighting level influences visibility. The nature of the relationship, however, is not fully understood, and therefore the lighting levels commonly provided by ADOT may be insufficient, or more than necessary, for acceptable safety levels. This has led the consultants to recommend that the proposed field experimentation involving lamp type and visibility be extended to include lighting level as a further variable. These three factors are intertwined, and further research is needed to understand their nature and influence upon driving safety.

4.2 IN-SERVICE SAFETY EVALUATION AND LIGHTING PERFORMANCE

The Topic Two work effort was conducted in accordance with all project requirements. However, it was unsuccessful in discovering any documentation relating light source type to crash experience. Since no agency reported useful data, the consultants therefore recommend a research program to collect the needed information. This should consist of a study involving three near-identical roadway sections, each lighted by one of the candidate light sources. These would be in-use roadways rather than a closed facility.

The consultants Topic Two work effort collected technical and cost data related to the three lamp types. A side-by-side comparison has been developed for the three sources for the lighting of a major roadway, using identical design specifications or each of the three. Each design was optimized for maximum pole spacing. The results were:

Lamp Type	Pole Spacing
400 watt HPS	276 ft.
180 watt LPS	176 ft.
400 watt MH	246 ft.

Primarily as a result of these pole spacings, HPS provides the lowest initial system cost. MH has 7% higher initial cost than HPS, while LPS is 41% more expensive than HPS.

Power costs for HPS and MH are essentially identical, but are 24% lower for LPS.

Considering overall operating costs, including maintenance, MH is 7% more expensive than HPS, while LPS is 12% less expensive. These values are based on a cost of 8 cents per kilowatt hour and will vary with this rate.

Life cycle costs, based on a 30 year life, are 7% higher for MH versus HPS, and are 17% higher for LPS versus HPS.

No recommendations are made to ADOT regarding lamp type. The issue is complex, with numerous interrelated safety and cost factors. The two research programs detailed in appendixes C and D are required before a basis for justification can be developed to recommend changing or retaining current usage.

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Note: Appendixes A and B provide a considerably expanded list of references.

APPENDIX A

Technical Report

LIGHT SOURCE COLOR AND LIGHTING LEVEL RELATED TO ROADWAY SAFETY

Reference: Research project SPR-522, Topic One

Lighting Sciences Inc.
7830 East Evans Road
Scottsdale, Arizona 85260 USA
Telephone: 480-991-9260
Fax: 480-991-0375

April 2003

APPENDIX A

LIGHT SOURCE COLOR AND LIGHTING LEVEL RELATED TO ROADWAY SAFETY

A1. INTRODUCTION

This technical memorandum has been prepared as part of task 2 of topic 522-1 of the project. It is an unbiased review of visibility, lamp color, lighting level and associated factors in relation to roadway lighting practice and standards. It also addresses the benefits, timeliness and efficacy of initiating further research in this subject, as this may relate to ADOT's goals and objectives.

In accordance with the requirements of the RFP, the main thrust of the work is in reference to high-speed roadways. It is anticipated, however, that the topic will be of significance in most roadway situations. The ranges of lighting levels found for a wide variety of roadways is therefore addressed.

Spectral distributions may be monochromatic, as in the case of low pressure sodium, (LPS), or non-monochromatic, as with high pressure sodium, (HPS), and metal halide, (MH), lamps. The issue of monochromic versus non-monochromatic sources is of importance in relation to light pollution. However, the topic is much broader. The actual form of the spectral distribution has been shown to have effects upon visibility, which may be related to accidents. The three sources are therefore addressed in this report in relation to their complete spectral distributions, rather than limiting the comparisons to monochromatic versus non-monochromatic effects.

The subject may have broader implications than just effects upon the driver. Bicyclists and pedestrians also may benefit from more favorable spectral distributions.

A2. TECHNICAL BACKGROUND

Adequate visibility on roadways at night is a significant factor in accident reduction, and in the facilitation of traffic flow. It is therefore highly relevant to determine what aspects of roadway lighting design affect visibility, and how visibility may be improved, within budgetary and technical constraints. Many lighting characteristics have been widely considered in establishing today's standards and practice, including light level, uniformity, pole spacing, luminaire type, photometric distribution, and lamp type amongst others.

When addressing all of these elements, however, it has been common practice to select lamp type based largely on economic factors. The factors include efficacy (lumens per watt), lumen maintenance over life, lamp life, lamp cost, cost of the associated luminaire and reliability. No serious consideration has been given to issues of Spectral Power Distribution (SPD) of a lamp's radiant output, and what effect differences in SPD might have in creating levels of visibility. If lamp color has been considered, it has usually been with regard to esthetics, identification of lighted object colors and issues related to astronomy.

Over the last five years, however, evidence has been produced that shows a potentially significant relationship between lamp SPD and visibility that in some cases may be significant. Two lamps that may have identical lumen outputs, but different SPD's may produce different levels of visibility. Metal halide, low pressure sodium (LPS) and high pressure sodium (HPS) all can be used to provide certain specified levels of lighting and uniformity by conventional means. The significant question is, however, what visibility will be produced using the different sources? A key related question is what level of lighting for the different sources is needed in order to provide equivalent visual performances? Exploration of this topic may develop methods to provide improved lighting practice, possibly at lower cost.

Methods of defining and measuring lumens date back to the 1920’s when the CIE V(λ) curve was established. (V-lambda is the eye sensitivity curve which relates visual response to the wavelength of the light source). However, vision scientists have known for most of the twentieth century that in fact the way in which the eye responds to color is dependent upon the lighting conditions.[1,2,3] Under certain conditions, the eye may perceive effects of high lumen output from a given light source. Under different conditions, the lumen output may be seen by the eye as much higher or much lower. Lamps, however, are given a rated lumen output as if the eye sensitivity to the light output of any particular lamp was always identical.

The problem is further compounded when we realize that all other lighting quantities, upon which we base our lighting design calculations, are based on the assumed lumen output of the lamp. These include lux and footcandles, intensity or candlepower, and reflected light, i.e. luminance, (candelas / sq. meter).

Because the eye varies in its response to different wavelengths of light under differing conditions, *true* assessment of the quantity and quality of light should address the eye's response under the prevailing conditions.

A2.1 Determining Lamp Lumens

Both in theory and in practice, the determination of lamp lumens involves knowing the SPD of the lamp and the visual response of the eye. Light is defined as radiant power *as evaluated by the human eye.*[1,2,3] Thus light is not simply defined as power in the same way as other forms of radiation. It is defined as the visual effect created by that power. To "simplify" matters, in 1935, the International Commission on Illumination (CIE) adopted the standard response curve, V(λ), which defines the spectral response of a typical person under "photopic" conditions. This is shown by the bold curve in Figure A1. "Photopic" refers to high light levels typical of daylight and interior lighting. Note also that the V(λ) curve is applicable only to the center small central area of the eye's field of view. It does *not* apply with high accuracy to off-axis viewing. (A separate function $V_{10}(\lambda)$ has been developed for this purpose.[3])

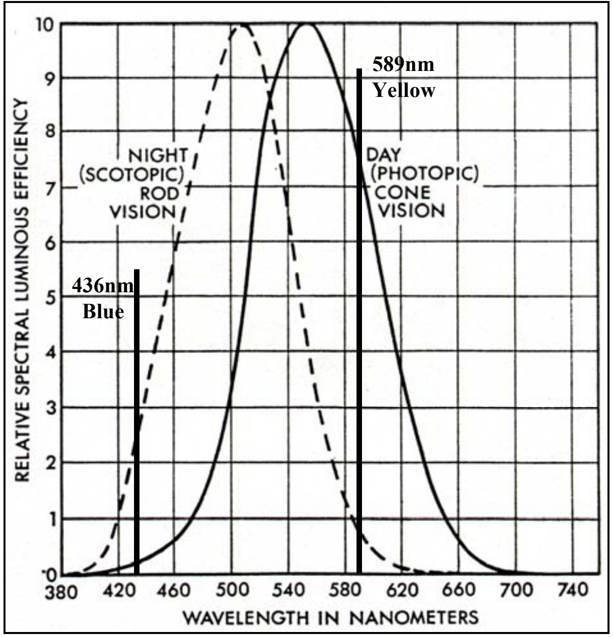


Figure A1. The V(λ) Curve (Bold) for Photopic Vision, and the V'(λ) Curve (Dashed) for Scotopic Vision

To determine lamp lumens, the power of the light at each wavelength, λ, in the visible spectrum is multiplied by the V(λ) value or eye sensitivity at the equivalent wavelengths. Then all of these multiplied values are summed to find the lumen output. This may be stated as:

$$\text{Lamp Lumens} = K \sum \text{Lamp Power}(\lambda) \,.\, V(\lambda) \,.\, \Delta\lambda$$

K is a constant to account for units.

A2.2 Applicability of the V(λ) Curve

So long as the V(λ) function is accurate and applicable to the viewing conditions being considered, the lamp lumen value is accurate. If viewing conditions change, however, and V(λ) is no longer applicable, the lamp lumen figure will not be indicative of the *effective* light output of the lamp. Likewise, the luminance of a surface will not give a true picture of the brightness of the surface as seen by the eye. This is fully recognized by CIE, and the need to use an appropriate eye response function is discussed in CIE literature.[3] For over 70 years, however, the lighting industry has used the V(λ) curve exclusively because of its simplicity, even though it often produces values that are not visually meaningful in a roadway situation.

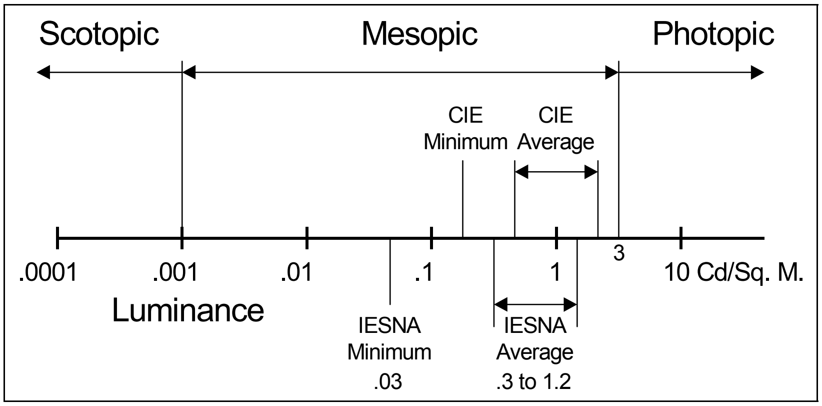


Figure A2. The Range of Photopic, Mesopic and Scotopic Light Levels.

High light level conditions, where luminances are generally in excess of 3 cd/sq.m, are termed “photopic" levels. The V(λ) curve applies to such conditions. But when the light level is very low, say below 0.001 cd/sq.m, the conditions are described as “scotopic.” This is typical of starlight levels at night. Between these two, conditions are referred to as “mesopic”, and apply to twilight and frequently used street lighting levels. Figure A2 illustrates the ranges, and also indicates the roadway lighting recommended levels, in terms of averages and minima, for IESNA and CIE practice.

Under scotopic conditions, the eye’s visual response changes dramatically (see Figure A1, dashed curve). This effect has been known for over a century, and is the well-known "Purkinje shift". The eye’s sensitivity to yellow and red light is greatly reduced, while the response to blue light is greatly increased. Clearly if lighting quantities have been determined using the photopic V(λ) curve, but viewing conditions are mesopic or scotopic, the lumen output value will not give an accurate indication of the true amount of light present, nor will calculated lighting quantities give a proper assessment of visibility. The extent of any deviations will be dependent on the roadway lighting levels. If higher levels than the IES recommendations are used, for example for TV surveillance, crime reduction etc., the V(λ) curve may be quite satisfactory.

The eye response does not shift suddenly from photopic to scotopic conditions. It undergoes a gradual change as light levels are reduced through the mesopic range.

The change in the eye’s spectral response can be explained by the presence of two types of receptors in the retina, rods and cones. Cones are active at high light levels and are most densely situated in the central part of the field of view. The spectral response of the cones corresponds to the photopic V(λ) sensitivity curve.

The rods are responsible for human vision at very low light levels, and are increasingly prevalent in the off-axis or peripheral field of view, away from our direct line of sight outside of the ± 1 degree foveal field. Within the fovea, there are no rods. As the light levels decrease, the cones become less active, the rods become active and spectral sensitivity gradually switches towards the scotopic response curve. Under roadway lighting levels, both rods and cones are active; their relative importance is dependent upon the lighting levels, and also the nature of the visual task, as will be discussed.

Of particular importance is the fact that different light sources have different spectral outputs; high intensity discharge sources have prominent outputs at certain wavelengths. Two important spectral lines are shown in Figure A1. The 589 nanometer yellow sodium line is near the peak sensitivity for the cones of the eye, but registers little effect on the rods. For the 436 nanometer blue line associated with mercury, a prominent line in metal halide output, the opposite is true, so this line strongly affects rod vision at night but counts for little in adding to the rated lumens. Use of the $V(\lambda)$ curve to predict light output under low light level conditions can lead to serious errors if the visual task relies heavily on vision by the rods.

It is apparent, therefore, that there is a problem related to conventional measurement and specification of lighting levels. Universal use of $V(\lambda)$ does not reflect the visibility that will be produced at mesopic light levels for visual tasks that are seen by the rods. It is the opinion of the authors that use of the $V(\lambda)$ curve as it is today is unlikely to change in the immediate future. It is therefore prudent to evaluate the impact of this practice as it relates to different light source types, and explore the possibility of developing corrective measures.

Because the distribution of rods and cones in the retina is not uniform, spectral effects will differ depending upon what part of the retina sees a particular visual task. The central field of view of ± 1 degree, the area of the fovea, consists entirely of cones. At increasing angles from the axis of the eye, the density of cones reduces while that of the rods increases. Spectral effects occurring as a result of rod response therefore have been found to be strongest for peripheral tasks. Some research has indicated no spectral response shift for on-axis tasks, although other research questions this conclusion.[4,5]

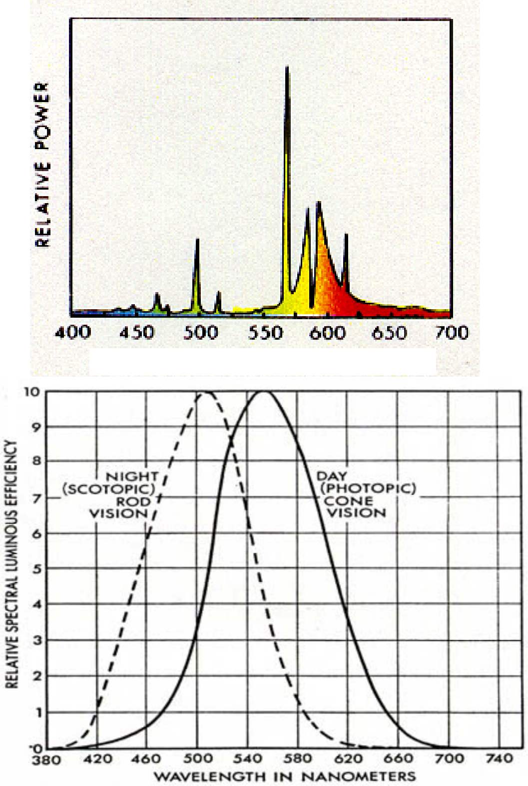
A2.3 Light Source Spectrum and Visual Response

The effectiveness of a particular light source in producing vision thus needs to take into account the lighting level and the color response of the eye appropriate to the task. This must also be related to the visual task, as the magnitude of the effects will be dependent upon the task type. To find the *effective* lumens of a light source at scotopic levels, for example, the lamp power at each wavelength is multiplied by the scotopic eye sensitivity (the dashed curve in Figure A1) at each wavelength. Then the values are summed. The *scotopic lumens*, therefore, will be very different from conventional photopic lumens. At mesopic levels, applicable to roadway illuminances, the effective lumens will be somewhere between the photopic lumens and the scotopic lumens.

A2.3.1 Sodium Lamps

Figure A3 shows the spectral power distribution of a typical high pressure sodium (HPS) lamp, drawn to the same wavelength scale as the eye sensitivity curves beneath it. The reason for the high lumen output of the HPS lamp immediately becomes apparent. The maximum energy output of sodium lies in a yellow region where the eye sensitivity is very high. Because the lumen output, by convention, has always been calculated as the amount of light as perceived by the eye under photopic conditions (the bold curve), HPS lamps have high lumen ratings. It is not so much that the sodium lamp produces a high power output, but rather that its energy peak is near the maximum photopic sensitivity wavelength of the eye.

Very little power output of the HPS lamp occurs at wavelengths shorter than the peak. Therefore the lumens as they apply to rod vision (the dashed curve) are much lower than the rated or conventional lumens.



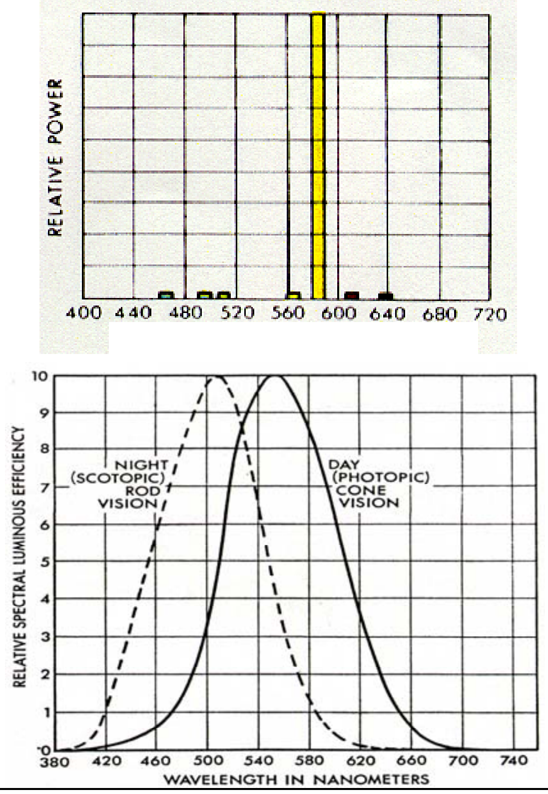
High Lumens (Photopic)

Lower Lumens (Scotopic)

Figure A3. Spectral Power Distribution of a Typical High Pressure Sodium (HPS) Lamp.

The effect with a typical low pressure sodium (LPS) lamp is shown in Figure A4. Virtually all energy output is in the yellow region, giving very high photopic lumen output. At low light levels, however, there is almost no energy output at wavelengths where rods are most sensitive. LPS lamps therefore have much reduced effectiveness for rod vision versus what their ratings suggest.

At the mesopic lighting levels relevant to roadway lighting, these effects will be reduced, as vision is normally achieved by use of both rods and cones. By how much will depend on many factors including the exact lighting level, the visual task, and other factors. Our understanding at this time does not allow a simple or single answer. In some cases the reduction may be close to that indicated by the scotopic response; in others there may be no or little reduction.



Very High Lumens (Photopic)

Very Low Lumens (Scotopic)

Figure A4. Spectral Power Distribution of a Typical Low Pressure Sodium (LPS) Lamp.

A2.3.2 White Light Sources

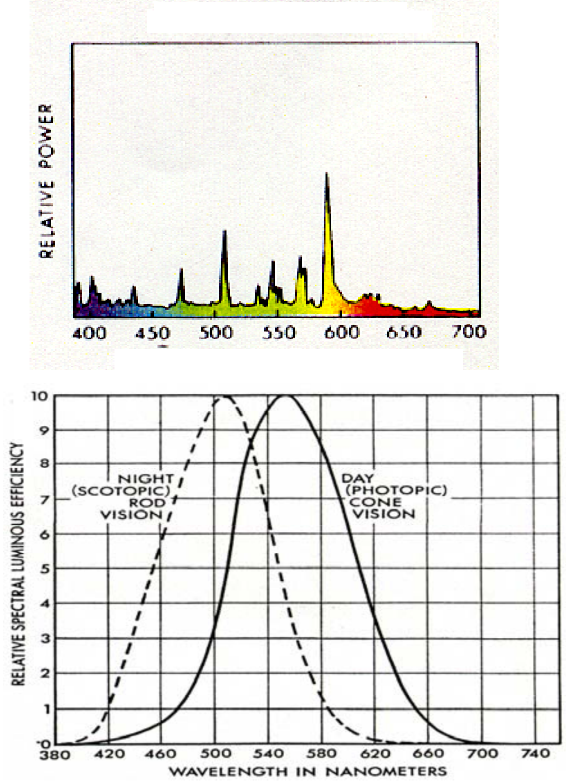
Sources that are generally described as “white” have a fairly evenly balanced output throughout the spectrum. In comparison to sodium sources, white sources have substantially increased output at shorter wavelengths.

Figure A5 shows the spectral distribution of a metal halide lamp. There are strong peaks in the blue, green and yellow regions. Note also that there is a considerable “continuum” of power output at all wavelengths, in addition to the peaks.

When the power output curve of the metal halide lamp is multiplied by the photopic sensitivity curve, a high lumen output is found, (although not quite as high as HPS). Using the dashed curve for the rods, it will be seen that some peaks in the metal halide power output lie in the high sensitivity region of the eye for low light levels. Moreover, the strong continuum of blue/green energy also lines up with the peak of the scotopic eye sensitivity curve. The net result is that the effectiveness of a metal halide lamp increases as the light level reduces versus what might be expected from its rated lumens. Furthermore, a strong yellow output exists to activate the cones.

This applies to visual tasks analyzed by the rods, which are most prevalent in the peripheral field.

In summary, under mesopic viewing conditions and for predominantly peripheral visual tasks, yellow sources have a reduced effectiveness versus what would be predicted from their lumen ratings, while the opposite is true for white light sources. All research shows that all sources investigated, including sodium and white light sources such as metal halide, can provide equal visibility if lighting levels are adjusted accordingly (excepting only where color perception is involved, discussed below.) High pressure sodium must be at a higher lighting level (measured conventionally, or photopically) than a white source, while lighting using low pressure sodium must be at an even greater level, for equal visibility. Further, some visual tasks are mediated primarily by the cone system, others by the rod system, and most by a combination of the two. Vision under mesopic conditions, the conditions relevant to virtually all outdoor lighting, uses both rods and cones to varying degrees and in complex ways. The subject is not well understood. Thus we cannot simply state that at low lighting levels, one source is better than another. We must ask "better for what tasks."



High Lumens (Photopic)

Higher Lumens (Scotopic)

Figure A5. Spectral Power Distribution of a Typical Metal Halide Lamp.

A3. LIGHTING LEVELS

The lighting levels used by ADOT and as recommended by other authorities are provided in the topic 2 technical report. These levels have been derived by consensus. There is no specific research that can be documented that is able to state in certainty what lighting level is needed for adequate safety under the many various conditions of nighttime driving. This is primarily due to the enormous complexity of the subject and moreover the difficulty of defining what constitutes adequate safety.

Much of the work that has influenced the development of the consensus standards has been based upon accident studies. A great many such studies have been conducted. Some are reviewed in the topic 2 technical report.

The data provided illustrate the visibility effects resulting from a given lighting level, measured photopically. Ideally, it would be useful to have some measure of visibility, rather than simply lighting level, to use as the basis for roadway lighting practice. There is no agreement on such a measure of visibility, at least as far as spectral effects are concerned. However, using the data presented later, it is possible to compare the lighting levels, measured in the conventional photopic manner, from two different lamp types respectively that are needed to produce similar visibility.

The subject, however, is very much complicated by the type of visual task, including its location, as discussed later.

The relative importance of lighting level versus that of spectral power distribution has been questioned. Research has indicated that, under some test conditions, the lamp SPD may be considerably more important than the lighting level.[4]

This is illustrated by Figure A6a, extracted from reference 4. This research involved a simulated highway scene where a pedestrian appeared at the roadside. The test subjects recorded, as quickly as possible, whether the pedestrian represented a hazard (pedestrian facing towards the roadway), or not, (pedestrian facing away from the roadway.) Tests were run at various lighting levels with several sources, and reaction times were recorded. Figure A6a therefore provides an example of the relationship of lighting level and lamp spectrum to reaction time.

At high lighting levels of 3 cd/sq.m or more, lamp type had no significant effect on reaction time. Below this level, however, reaction times were longer for sodium sources than for white sources. This effect becomes progressively greater as the light level is reduced.

Figure A6b shows the same data for HPS and metal halide, with construction lines added to assist in exploring the relative effects of light level versus those related to lamp type. Consider as an example the IESNA recommended average luminance for a freeway class A, which is 0.6 cd/sq.m Figure A6b indicates that, for HPS, this will produce a reaction time of approximately 840 msec, for the conditions tested. If this lighting level were to be considerably increased, say by 50% to 0.9 cd/sq.m, the reaction time decreases to roughly 775 msec, a decrease of roughly 7.7%.

However, if the 0.6 cd/sq.m lighting level is retained and a metal halide source is used, the reaction time becomes 690 msec for the same test conditions. This is a decrease in reaction time of 17.9% versus HPS. Thus changing the lamp type has more than twice the effect as a 50% increase in light level in this example.

As shown by the dashed curve on Figure A6b, to achieve the reaction time of 690 msec that was produced by 0.6 cd/sq.m using MH, a luminance of 1.08 cd/sq.m is needed for HPS, all other factors being equal.

Thus is can be seen that there is a trade-off between visibility, lighting level and lamp type. For the type of visual task investigated in this example, if a certain reaction time were required, it could be produced using all three sources, but different lighting levels would be required to achieve this. Figure A6c illustrates an example.

Figure A6c indicates a horizontal line for a reaction time of 775 msec. This corresponds to a luminance level of 0.9 cd/sq.m. using HPS, a commonly used lighting level. Dropping the dashed vertical line from the MH curve indicates that this same reaction time can be achieved using MH at a luminance level of 0.17 cd/sq.m., a reduction of 81% versus HPS. The dashed vertical line from the LPS curve shows that a luminance of 1.30 cd/sq.m. of LPS will be needed for the same visibility. This is an increase of 44% versus HPS. Thus all three sources can be used to produce given visibility (within limits), but different lighting levels, measured photopically, are required to do so.

This example is for illustration of the principles only, and the extent of the applicability of the above is dependent on several factors. It must be further understood that improvements to visual performance due to SPD effects are limited to those achievable with available lamp types, while the improvements achievable with changes to lighting level are limited only by the lighting levels achievable and the nature of the lighting level vs. response curve. If the lighting level is limited to 0.1 cd/m^2, reaction times can range from 1200 to 800 msec using the illustrated lamp types. By varying the light levels, reaction times can vary from 1200 to 600 msec, or even a larger range. Economic issues, however, are of great importance, and tend to limit what lighting levels can be provided in practice.

There are many ramifications to be considered, particularly with respect to the visual task, as discussed below. However, the importance of SPD should not be underestimated. It can be a highly significant factor.

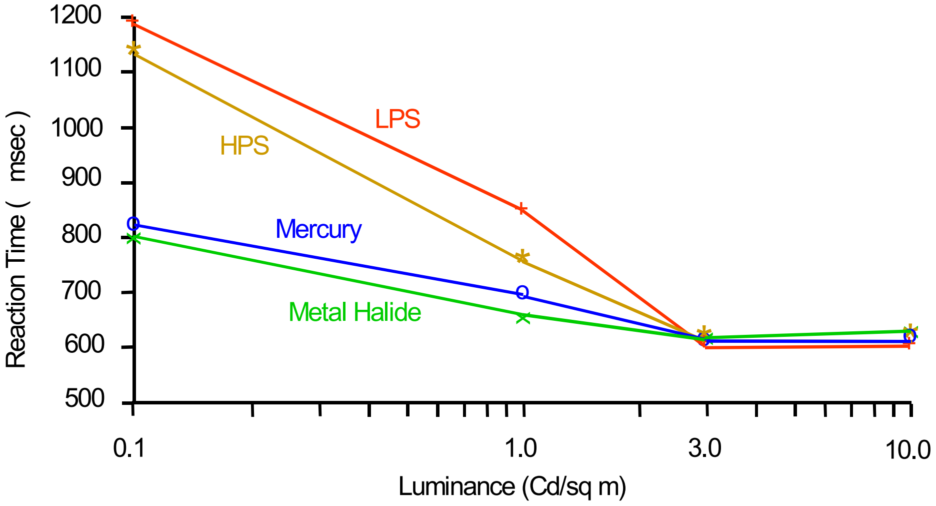


Figure A6a. Lewis Research Data for Four Sources.

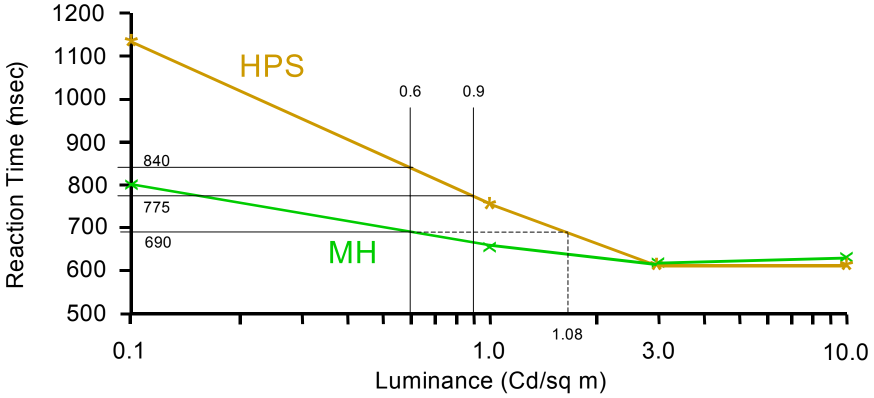


Figure A6b. Reaction Time Projections

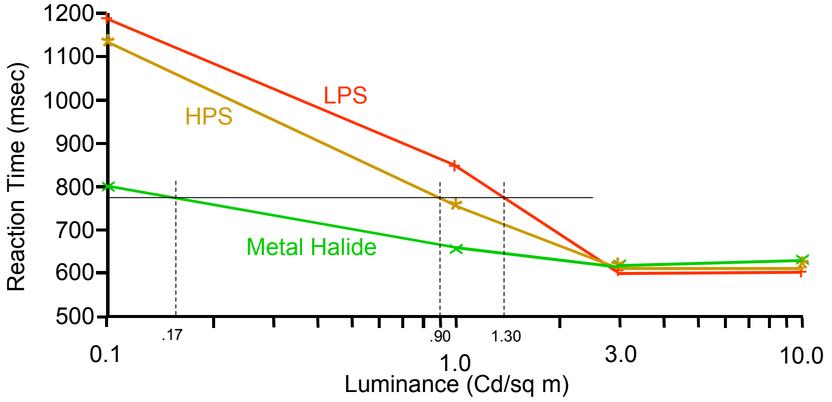


Figure A6c. Luminance Levels for a Fixed Reaction Time.

A4. ROADWAY LIGHTING – THE VISUAL TASK

For many visual tasks, for example, reading and writing, the nature of the task is predictable and its location is known. The eye scans the page and the center of the field of view, the fovea, is used to read. In other situations, however, the entire field of view is under constant assessment by the eyes and brain. In a driving task, a great deal of information comes from outside of the small central field of view. As an example, a pedestrian stepping off the curb may be initially detected in the peripheral field of view, followed by the driver directing his/her view to more clearly discern the hazard. The first sign that a hazard is occurring, however, may be obtained via off-axis or peripheral vision. Olson provides a summary of this topic in his book on driver perception.[6] There is however debate and much uncertainty on the relative importance of foveal versus peripheral vision for driving tasks, with some authors feeling that foveal vision is of primary importance.[7] However, others state "Visual acuity is only weakly related to crash involvement, whereas peripheral vision appears to play a more critical role."[8] (Visual acuity is based on foveal response).

Until recently, it has been assumed that the spectral effects under discussion apply only to objects seen in the off-axis field. This is because rods dominate the off-axis portion of the retina, while cones are concentrated in the fovea, or central area of the retina. In fact, exactly in the center, no rods are present.

Two important factors require consideration. Firstly, off-axis tasks are extremely important at night, and are believed to be closely related to issues of safety. Secondly, and possibly surprisingly, there is evidence that rod vision is important for almost *all* visual tasks, even those that are looked at directly.[4,9] However, there is need for much further work in this area, involving analysis of viewing directions and the nature of roadway visual tasks.

New vision research is being conducted to define the characteristics of nighttime visual tasks.[10] This is part of a significant program involving the Illuminating Engineering Society of North America, the New England College of Optometry, and various other organizations, (including the consultant for this ADOT effort). The work is based on the analysis of "spatial frequencies" found in the visual task. A highway sign is an example of a task having high spatial frequency: the letters and background differ sharply in luminance, and differences occur rapidly from point to point over the face of the sign. The boundary between the berm and a deer by the side of the roadway, however, is a visual task of low spatial frequency: the luminance difference between the animal and its background is not dramatic and it does not repeat frequently and rapidly across the scene.

We have been informed that preliminary research results from this program indicate roadway visual tasks at night consist almost entirely of low spatial frequencies, while high spatial frequency tasks are limited to reading signage and the vehicle's instruments. This would be in agreement with findings that have indicated that peripheral tasks are more important than foveal tasks in accident avoidance.[8]

If found to be correct, the significance of these preliminary findings will be profound, because the cone system of the retina is constructed to provide visibility of high spatial frequency tasks, while the rod system is superior for low spatial frequency tasks at low lighting levels. These findings suggest that, while there is insufficient light at night for the cones to function with full efficiency, in fact, a high level of cone activity may be unnecessary because it is the rod system that primarily produces nighttime visibility. Much work is yet to be done in this subject, and careful examination of the data is necessary. It is of note, however, that the preliminary information appears to explain why, in previous research where the test subjects moved their eyes to look directly at a pedestrian to judge which way the person was facing, effects were found that would be expected only from a significant use of rod vision.[4] A possible explanation for this is because of the continuous movement of the eyes, objects are constantly being scanned. Under mesopic conditions, it has been theorized that most of the visual input from an object that is straight ahead is from the rods which lie just outside the dead-center of the visual field. Therefore even for tasks which we look at directly, at mesopic levels, most of the visual input may be from the rods and not the cones. Again, this appears to support the findings of others.[8]

It should be noted that this information is controversial. There is insufficient research available for there to be general agreement on the topic. Fortunately, work is being conducted although the great complexities are recognized.

A5. MAGNITUDE OF THE SPECTRAL EFFECTS

Much research is now available that reports on experiments to determine the practical significance of the spectral effects. Results indicate that the effects can range from zero to very significant.[4,5, 9,11-15] At high lighting levels, typically higher than would be used for outdoor lighting, mesopic effects do not occur, as vision is photopic. Even under high mesopic levels, the effects may be small, becoming progressively greater as the light level reduces. Some tests involving small on-axis tasks, even at mesopic levels, have shown an absence of the spectral effects under discussion. Presumably cone vision is used for such tasks. Larger on-axis tasks have shown strong spectral effects, suggesting the use of the rods. Thus the complexity of the subject is illustrated. Not only are the spectral effects dependent upon lamp SPD and lighting level, but also upon the nature of the task itself.

Unfortunately, there is not definitive information to allow us to assess the relative importance of on-axis and peripheral tasks, and of large and small hazards. We therefore do not know the relative importance of the factors involved. This emphasizes the pressing need for research to investigate the subject.

Lewis has reported results of reaction time tests where detection of a pedestrian was conducted using metal halide, mercury, high and low pressure sodium lamps.[4,9] As an example of Lewis' data, he found an approximately 50% increase in reaction time for sodium sources versus metal halide, at a luminance level of 0.1 cd/sq.m. (Figure A6a.) Such a lighting level is found in dark locations in residential streets. At a relatively high lighting level of 1 cd/sq.m, typical of major roadways, Lewis reported an increase in reaction time of approximately 15% for HPS versus metal halide, and 25% for LPS versus metal halide. Such increases in reaction time can be significant at typical highway speeds. The research indicates that sodium sources can produce reaction times equal to those for white light sources, but only if luminance levels are increased versus the white sources.

The Lighting Research Center (LRC) at Rensselaer Polytechnic Institute has reported dramatic improvements in the visibility of slightly off-axis small tasks under white light versus sodium.[11-15] LRC, and other research groups, have reported no increase in visibility associated with the use of white light versus yellow in cases involving small on-axis tasks.[5] It is presumed that the fovea, consisting of cones, is used to provide the visibility of such objects, and therefore no benefit would be expected. However, given the research results of Lewis, where spectral effects were highly significant in determining which direction a pedestrian was facing when observed directly on-axis, it must be debated to what extent small tasks with high spatial frequency as used in these experiments are truly representative of typical roadway tasks. It appears logical at this point to assume that various types of tasks exist, including those that are analyzed by the fovea, those that are best perceived by the rod system, and those that are viewed by some combination of the fovea and peripheral retina.

It can be seen that there is conflicting data. Until more is known about the nature of roadway visual tasks, the effect of lamp spectral distribution cannot be definitively stated. We can say, however, that no research results indicate *lower* visibility using metal halide sources, and some report much higher visibility, for equal lighting levels. Where a positive impact in using metal halide is indicated, results show a lower lighting level can be used while maintaining equivalent visibility. To the extent, however, that foveal tasks are important on roadways at night, cone vision is significant. In such a case, lowering the lighting level is likely to reduce the visibility of such tasks.

Any visibility benefits to be obtained by converting from sodium to metal halide lighting, and retaining present lighting levels, cannot be quantified. If recent suggestions that roadway tasks are of low spatial frequency are valid, substantial visibility increases for such tasks are to be expected, along with commensurate safety improvement. To the extent that high spatial frequency tasks exist, there is likely to be no improvement for such tasks.

A6. THE EFFECT OF HEADLIGHTS

The foregoing has discussed effects resulting from lighting levels that are assumed to be generated by the fixed roadway lighting system. However, in reality, headlights will be present, and when used on low beam will provide visible illumination typically to a distance of about 100 to 120 feet, when roadway lighting is present. This is because low beam headlights are aimed downwards from the horizontal.

Reflected luminance created by headlights will affect the state of adaptation of that portion of the retina which receives the image of that lighted area. With this increased state of adaptation, rod response will be reduced and cone response will be increased.
It is significant to note, however, that the state of adaptation of the remainder of the retina will be essentially unchanged. This is because the retina undergoes localized adaptation, that is, each point in the retina is adapted at any given instant to the image it is receiving. This image will be constantly changing because of eye movements. Accident avoidance is helped little, if any, by image detection in an area up to 120 feet in front of a vehicle, except possibly in low speed situations. This is because for a typical reaction time of 1.5 to 2.5 seconds, the driver is unable to take evasive action before striking the hazard. The state of adaptation of this part of the retina is therefore largely irrelevant as related to detection of potential hazards beyond this limited area of the roadway.

It should also be noted that these localized adaptation effects change rapidly. "Transient adaptation," which occurs in approximately 0.1 seconds, ensures that any part of the retina is not adapted to a state related to luminances blended over a much larger area.

A7. GLARE

Little work has been published that relates glare from a roadway lighting system to lamp spectral distribution. It has been postulated that glare will be increased by lamps that have high short wavelength output, i.e. white sources, because of the nighttime spectral sensitivity shift described in this report. It has been argued, however, that because the retina selectively adapts, that part of the retina exposed directly to a bright light source at a given instant will be photopically adapted. If this is correct, it will be affected strongly by a yellow-rich source. Disability glare, caused by light scattering in the eye, imposes a low level of veiling luminance on the scene. This may be worse from a white source if the parts of the retina affected are mesopically adapted.

Berman et al have studied the relationship between glare and spectral distribution.[16] They found that a scotopically enhanced source produced less discomfort glare when compared to a scotopically deficient source, contrary to expectations. The sources tested were large area sources, and it is not known whether the results are directly applicable to roadway luminaires.

A8. CHROMATIC EFFECTS

A8.1 Color Contrast

It has been indicated that lamp color and lighting level play an important role in creating visibility. However, something else needs to be considered which has been almost entirely overlooked in past lighting design.

A surprising fact is that in vision research and illuminating engineering, most work is done on the assumption that we live in a monochrome world. Research on contrast sensitivity, reaction times and visibility levels is almost entirely based on the detection of targets which are black, gray or white on backgrounds which are also black, gray or white. Even in assessing visual performance of tasks under different lamp spectral distributions, research work has usually considered only tasks and backgrounds of various shades of gray. Results of such monochrome work have led to most, if not all, of our lighting level standards.

These limitations may be significant. Figure A7 shows a series of gray targets on three different gray backgrounds. In the uppermost array, targets are visible by negative contrast, while in the lower array they can be seen by positive contrast. But both arrays have low visibility. The middle array of targets is essentially invisible against the medium gray background. Targets and backgrounds of shades such as these have been used throughout vision research. If we add real world colors to the targets, however, all targets are clearly visible, Figure A8.

If the luminance of the background and any one of the colored targets in the center row of Figure A8 is measured, and contrast is calculated in the conventional way, the contrast will be zero or extremely low. The contrast will probably be lower than the eye's threshold contrast, so in accordance with universally accepted theory, the targets are invisible. Clearly, however, the targets are not invisible.

Illuminating engineering theory overlooks this basic principle: color contrast can be an important element for providing visibility in real world situations. Luminance contrast is only part of the story.

It is intuitive that by adding color contrast to a visual scene, visibility is increased. If we add very little color, the visibility increase may be small, while adding full color can produce a significant visibility increase. A white light source will add more color to a colored scene than a light source which is color deficient in some parts of the spectrum. It seems reasonable to conclude that, if color is a visibility-producing component in a scene, metal halide sources will inherently create a greater increase in visibility through color contrast than spectrally deficient sodium sources.

This is illustrated in Figure A9. While Figure A8 illustrates target appearance under white light, Figure A8 is representative of high pressure sodium lighting. The targets are still visible, but not as highly visible as with the white light source. In real world situations where objects may or may not be detected, it is desirable to increase visibility, and to do so without increasing the lighting level. Improved color contrast is one such method.

Figure A10 is similar to Figure A8, the colored target array under white light. In this case, however, the luminance levels have been reduced. The HPS lighting in Figure A9 has a roughly 20% higher luminance than the white light used for Figure A10. The targets are still visible. In fact, even under this reduced level of white light, the targets can be seen as clearly as under the higher level of HPS lighting.

The targets shown in these figures have fairly high color saturation in order to clearly illustrate the effects. Real world objects frequently will have less color saturation, (desert dirt), but in some cases may have high color saturation, (grass, vehicles, clothing).

We do not yet have data to calculate the visibility improvement produced by increased color contrast. It is not known whether color contrast is highly significant or a minor effect in producing visibility, because data are unavailable. No matter what level of importance might be assigned to it, it must be considered along with all other factors when assessing the overall effect of spectral distribution on visibility. A research program is needed to increase our understanding of this factor.

A8.2 Color Recognition

Yet another factor to be considered in lighting for security is the ability to recognize and accurately name the colors of objects. Such objects may be a vehicle which has been involved in an accident, or a person's clothing.

Because sodium lighting does not produce sufficient light in certain spectral regions, the reflected light from colored objects is spectrally distorted. Figure A11 illustrates three selected colors, photographed under white light and high pressure sodium light. Colors such as yellow, and to a lesser extent, red, show up reasonably well under sodium lighting, see figures A8 and A9. Blue and green objects, or objects of a color where there is a moderate or high blue or green content, have a mud appearance. Under some circumstances, this effect may cause difficulties.

It has been suggested, however, that this factor may not be major, because the lighting of a scene is rarely accomplished using only sodium sources, and that only a small amount of white light is required for adequate color recognition.[17] Nighttime scenes are often lighted by a combination of sources, including headlights.

A8.3 Color Preference

An article entitled "Fringe Benefits" was written by Monik Nehra in May 1999, which compared HPS to MH.[18] In this article Nehra evaluates the use of outdoor lighting to satisfy a variety of factors such as safety, glare, color rendition, aesthetics and cost. A study that was referred to in this article was conducted by the Kansas City Power and Light Company, (KCPL). In this study KCPL set up a series of experimental residential street lighting system configurations in the field using metal halide and high pressure sodium lamps. Each system used a variety of different luminaires, designs, pole spacings and mounting heights. The findings of this study found that residents preferred metal halide, as opposed to the local officials who had a higher preference for high pressure sodium. This is an interesting divergence; it suggests that the public would prefer whiter light.

This article also made an argument that an interaction exists between light level and the color rendering index (CRI) of a light source in terms of people's perception of security. It is suggested that, at lower light levels, (such as those used for roadway lighting), a light source with a higher CRI provides a higher sense of security. Metal halide has a CRI of 65 or greater, high pressure sodium has a CRI of 22 and low pressure sodium's CRI is zero. Nehra goes on to make the recommendation, that at least for security lighting, a light source should have a CRI of at least 65. It is not known to what extent, if any, these conclusions apply to roadway lighting, but they are of interest in suggesting that SPD is related to more than just visibility.

A9. OTHER FACTORS

Several other issues are under consideration regarding lamp spectral effects, which are addressed below.

A9.1 Observer Age

As the eye ages, there is a tendency for the lens to become yellow. This again will influence the relative perception of scenes lighted with light sources of different spectral distributions. It may be postulated that yellow sources will provide greater visibility, as the rays will be transmitted through the lens more readily. On the other hand, the rods in the peripheral field are best stimulated by shorter wavelengths. Therefore it may be necessary to use sources having high blue-green content to stimulate the rods in the older eye, otherwise a gradual loss of peripheral vision will occur with age. The fact that a greater proportion of yellow light can be transmitted by the older lens may not be particularly relevant if the sensors that produce most visibility require stimulation by blue-green light.

Quantification of such effects with regard to the spectral distribution of various light source types has not been performed in detail. Any future research program must take such factors into account to ensure that possible changes to lighting practice, while apparently beneficial to the younger driver, are not of detriment to the older driver.

A9.2 Pavement Reflectance

The spectral reflectance of the pavement may influence driver visibility. A surface having a yellowish coloration is more attuned to reflecting sodium light, whereas a surface with greenish coloration will reflect metal halide light more strongly. Thus the reflected luminance towards the driver will be affected differently for different road surface coloration and for the different sources.

One study by Adrian in Canada has briefly investigated this factor.[19] The results indicate an increase in reflectance at longer wavelengths, i.e. yellow and red. This therefore would favor sodium sources. The work, however, did not attempt to determine whether such pavement characteristics are geographically widespread. Any future research program should investigate this matter further, and should determine whether such effects are found for typical Arizona pavements of black (new asphalt), medium grey (worn asphalt and Portland cement Concrete), light grey (new Portland Cement Concrete), and rubberized asphalt.

A9.3 Accuracy of V(λ)

Much research has been done since the V(λ) curve was established to allow us to better understand cone vision. Various investigations have developed more advanced functions to describe how the eye responds to different spectral distributions. These functions are based on experimental data and are modeled on modern knowledge of the physiology of the eye; they produce different results from the V(λ) function. Professor K. Houser of the University of Nebraska has reviewed these functions and applied them to today's light sources.[20]

Houser's work evaluates different types of metal halide and other white sources and compares the brightness produced on an equal conventional lumen basis. Each metal halide source produces a greater brightness versus HPS when compared on this basis. His results show that a metal halide source (of the sodium-scandium type) produces about 8% higher perceived brightness per conventional lumen than HPS. For another metal halide type (4,000 Kelvin Na/Tl/Dy/Li type), the figure is 5%. This is for cone vision in the central field of view, and is applicable to all light levels. (Peripheral vision at night may be greatly increased with metal halide, for a given lighting level, as described earlier.)

Work by Dr. Sam Berman of the University of California has involved observers judging the brightness of areas lighted by different sources.[21,22] Sources which have a high scotopic (blue-green) light content appear brighter to most persons. He found this to be true even when the blue-green rich source was producing *less* luminance as measured by a meter. However, this work was conducted at lighting levels typical of offices where cone vision is used. It is not known to what extent, if any, this may apply to roadway lighting levels. This further serves to emphasize that even for tasks where it would normally be assumed that only the cones would be used, there is apparently a strong influence in brightness perception resulting from responses which are usually associated with rod vision.

A10. SAFETY AND VISIBILITY

The forgoing discussion has addressed spectral effects as related to visibility. It does not address safety directly. Logically, however, increased visibility will provide increased safety. Document CP-31-02, Value of Public Roadway Lighting, now under development by IESNA, and its predecessor CP-31-1989, provide extensive references regarding the connection between roadway lighting, visibility, safety and security.[23] CIE has also produced an extensive document on the subject.[24] Reference 25 also addresses the matter.

Government sponsored research also indicates the relationship between accidents and visibility. Many useful references are provided in references 23 and 24.

Certain experiments at LRC used a driving simulator, and indicated that improvements in visibility, which are produced by higher effective (mesopic) luminances resulting from lamp spectral effects, reduce accident rates.[12,13]

While a connection clearly exists, the precise correlation between specific levels of visibility and accident rates has not been ascertained.

A11. ASTRONOMY AND LPS

Much information is available concerning outdoor lighting and its negative effects upon astronomical observations.[26]

There is a desire on the part of astronomers to encourage the use of low pressure sodium sources, as such near-monochromatic radiation can be largely filtered out at the observatories. Any considerations regarding light source use near observatories must be cognizant of these wishes.

A future task that is part of this current research topic is the evaluation of light source characteristics related to the many technical and cost issues involved. A future report will address such information. As related to visibility, however, the following points can be made regarding LPS:

- LPS is a practical light source, and can be used to provide the lighting levels and uniformities as required by ADOT. The significant question, however, is "can LPS provide the required levels of *safety* required by ADOT? Research conducted at the universities has indicated a strong correlation between the visibility of certain objects, largely but not exclusively peripheral tasks, and the SPD of the light source.[4,9,11-15] Efforts were made by the involved researchers to provide realistic test conditions, such that the results could reasonably be expected, to some extent at least, to apply to nighttime driving conditions. It may further be reasonably expected that there is a direct relationship between visibility and safety. If there are any practical roadway nighttime tasks that embody similar characteristics to those used in the research programs, it is logical to believe that practical safety involving these tasks will be influenced by lamp spectral distribution. Safety, for such tasks, will be reduced by the use of sources having a predominantly yellow output, all other factors being equal. However, it is generally accepted that safety can be improved by use of an increased light level. If the LPS lighting level, measured in conventional footcandles, is increased sufficiently to offset the reduction in visibility of these tasks caused by the spectral distribution, safety can be maintained. If, however, LPS lighting is used to provide similar levels of footcandles as in use today for other sources, the preponderance of available evidence suggests that some visual tasks will be affected, visibility of these will decrease, and safety will be compromised.

- For visual tasks analyzed solely by the eye's cone system, (ignoring the effects of color contrast), a given lighting level of LPS can be expected to produce equal visibility to metal halide or HPS.

- For visual tasks analyzed by the eye's rod system, LPS will produce a lower level of visibility than metal halide or HPS, when the lighting design is based on a given (photopic) lighting level. The extent of the visibility reduction will be dependent upon the light level, with the visibility reduction versus the other sources becoming progressively greater as the task luminance falls, (see next section).

A12. COMPARING RESEARCH DATA

The basic approach of this technical memorandum is first to evaluate lamp type versus the visibility created for identical lighting levels. From this, if future research can definitively show that the documented visibility differences between the sources are applicable to roadway lighting tasks, then conclusions can be drawn regarding lighting levels. In comparison to today's most common source, HPS, for equivalent visibility, a decreased level of metal halide might be used, while an increased level of LPS might be necessary. It is hoped that future research, over time, will resolve these questions.

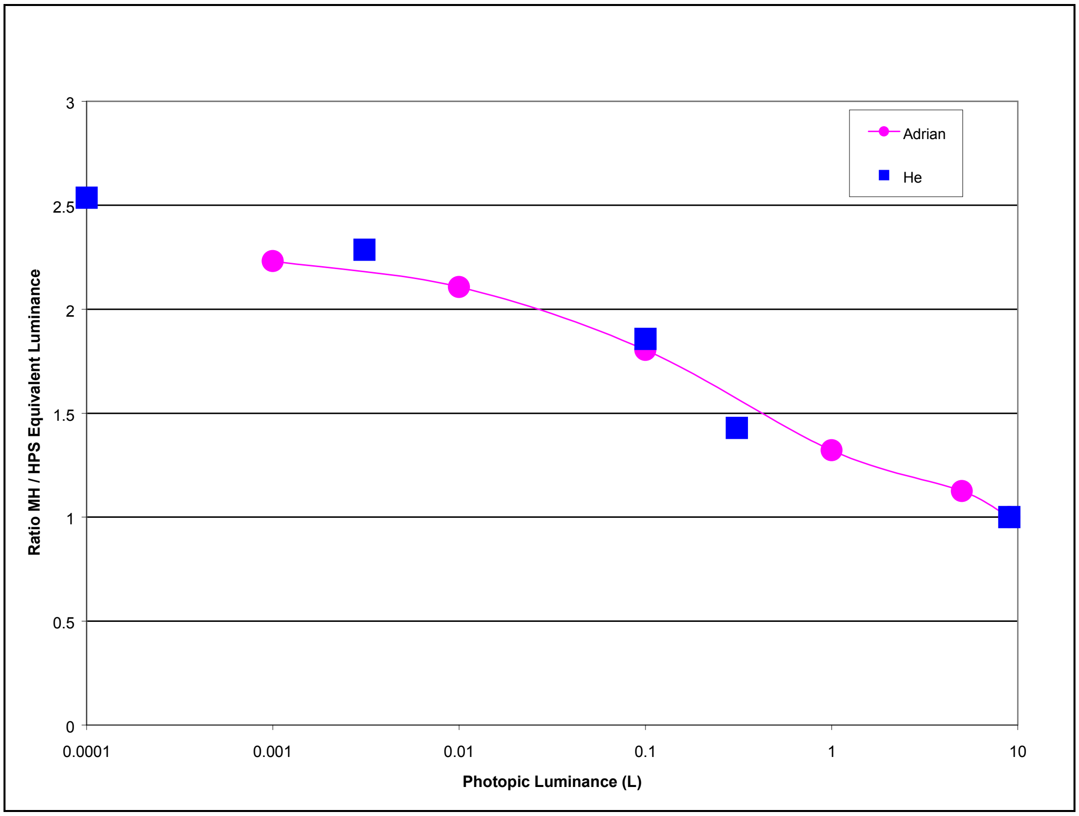


Figure A12. Comparison of Adrian and He Data. (Courtesy Dr. Werner Adrian)

This topic has been studied under the auspices of the International Illumination Commission, CIE. The data were produced primarily by Kinney and have been analyzed by Adrian.[27,28] The primary, although not only, basis for the CIE data was "brightness matching", a procedure where the apparent brightnesses produced by various colors are investigated at different light levels. This is not necessarily a measure of visibility. However, work at LRC involving visibility and reaction times has been shown to result in similar conclusions to the CIE data. At this time, therefore, the CIE data appears to be useful for comparing relative light levels between sources for equal visual results.

The concepts of "Spectral Correction Factors", SCF and "Lumen Effectiveness Multipliers", LEM, have been developed.[29] These are factors, which are dependent upon light level and the spectral power distribution of the source, that can be used to correct a calculated photopic or conventional lighting level to an equivalent level based on the visibility or brightness produced. The use of such factors, if agreement of the values were obtained, would allow the use of different lighting levels for different sources, on the basis of equivalent visibility.

Average roadway lighting levels generally fall in the range of 0.3 to 1.2 cd/sq.m.[30] The curves in Figure A12 show a factor for the center of this range of roughly 1.4 for metal halide and 0.75 for HPS. This indicates that, on this basis, roughly half the lighting level of metal halide versus HPS can be used to produce equivalent visibility. This is intended to be illustrative only; the actual factor for any given location will be dependent upon the lighting level at that point. Note that minimum levels may fall as low as 0.03 cd/sq.m.

The multipliers will show a less dramatic effect at high roadway lighting levels, and a greater effect at lower levels. As a further consideration, it may be argued that, under a given lighting system, accidents are more likely to occur in the dark areas; a pedestrian is less likely to be detected if silhouetted against an area where the lighting level is lowest. That is why lighting standards address uniformity, to ensure that levels in certain part of the roadway do not fall too far below the average.[30] At locations of low lighting levels, the metal halide multiplier versus that for HPS is at its greatest, and therefore the increased safety created by the white source is highest at just the point where it is needed the most. (References 23 and 24 provide illustrations relating accidents to lighting levels).

A13. FUTURE RESEARCH

A13.1 The Need for Future Research

This memorandum describes the relationship between light source type, lighting level, visibility, and anticipated safety. The foregoing has indicated:

- Well-accepted vision theory predicts that for certain types of visual tasks under low lighting levels, the visibility created will be greatest for metal halide and lowest for LPS if lighting levels are not adjusted to compensate for spectral effects.
- Laboratory studies have documented data that confirms the above theory.
- Research indicates that some roadway visual tasks are of a type that will benefit from the use of white sources, assuming equal light levels as conventionally measured.
- If certain important tasks do not benefit from a change to white light, then a reduction in lighting level and energy use may cause a reduction in visibility and safety.
- No research program apparently has conducted actual testing of these effects in the field.

It can be concluded, therefore, that while there is much evidence to suggest white light may produce safety benefits over sodium light if lighting levels are not adjusted for SPD effects, there is still a major unanswered question: do the benefits accrue for practical roadway visual tasks? If research is conducted and is able to answer this basic question, and in fact the theorized benefits can be shown to be real, the benefits may be major. Without such a research program, the subject is likely to involve more laboratory studies and more information, but without ever determining the true applicability of the work in field applications.

The consultant therefore advises ADOT to implement a research program to provide the first and definitive field study, thereby settling the issues and questions that are presently prevalent.

A13.2 Benefits of a Future Research Program

The numerous potential benefits include:

- The future research program will be designed to collect data relating lamp type to safety. As such, it will presumably be the first to do so. While laboratory studies indicate that increased safety at equivalent lighting levels may result from selection of a spectral distribution other than that which is currently widespread, the adoption of new policies on the matter require that there be conclusive evidence that increased safety or other tangible benefits will be produced.

- Any safety benefits that occur as a result of this research will lead to accident reduction, in itself producing significant economic benefits.
- A program that produces safety benefits in line with expectation given by the laboratory research will serve as confirmation of the research. It will further provide verification of the nature of the visual tasks in roadway at night. Thus the body of knowledge on this subject will be enhanced.
- If the laboratory work and theory is confirmed, this will also serve to confirm another assertion, that reduced lighting levels of a preferred spectral distribution will maintain a level of safety at least equivalent to current practice. If, however, the research project does not serve to confirm other studies, it will nevertheless have provided an important contribution, and will thereby have provided very significant information.
- Applying reduced levels of lighting while maintaining safety may produce reduced operating costs through energy reduction.
- Data will be developed that will allow comparisons to be made of the reduced operating costs due to energy reduction versus possible increases in cost that might occur due to reduced lamp life or other negative aspects of using different light sources. By providing a more complete understanding of the technical and economic tradeoffs, ADOT will be in a much improved position to adjust specifications and practices for optimized solutions.
- With respect to light pollution, the study will confirm or deny assertions that LPS is a good choice of light source. If, in fact, no significant detrimental effects can be attributed to the use of this source, its use in the vicinity of observatories will be supported.
- ADOT will establish a leadership position in what is widely seen as the most critical issue in the outdoor lighting industry today. Any benefits, safety-related or economic, occurring from this program will be available to lighting practitioners both nationally and internationally.

The significance of this work cannot be overstated.

A13.3 Timeliness and Efficacy of the Future Research

HPS and LPS technology are relatively static. Metal halide technology has improved substantially over the last few years. Two new families of metal halide lamps have been developed, the pulse-start lamps, and the ceramic arc tube lamps.

Metal halide sources have always suffered from shorter life, lower lumen output and poorer lumen maintenance than sodium sources. The two new ranges of these lamps represent major advances in their life and performance.

It is therefore very timely for a research program to develop the suggested comparisons, as metal halide technology may now have reached a point where it is economically feasible for roadway lighting. This is particularly so if results indicate that reduced lighting levels are appropriate when using this source.

More significant improvements in metal halide sources are anticipated in the near future, and are likely to be available within roughly the same time frame as the results of the recommended future research program.

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Figure A7. Monochrome Targets, White Light

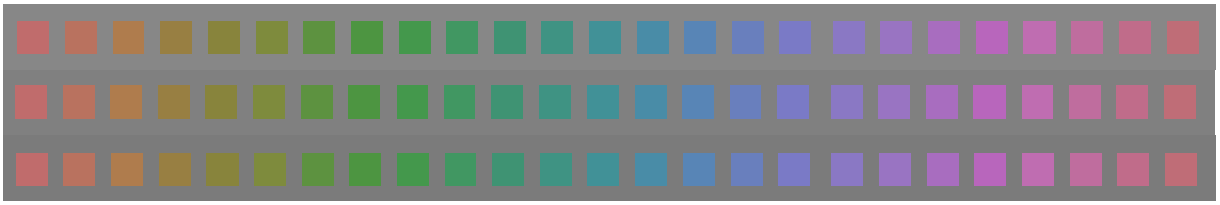

Figure A8. Chromatic Targets, White Light

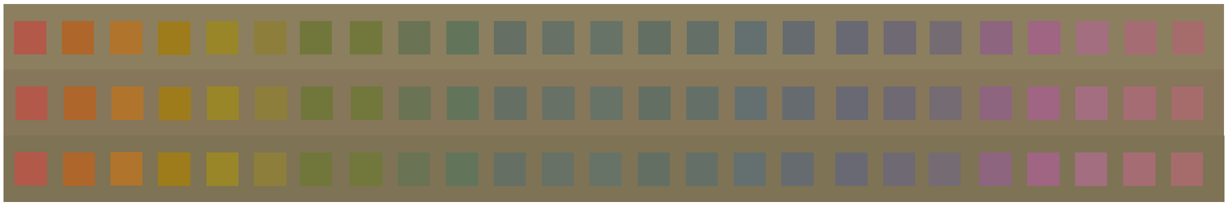

Figure A9. Chromatic Targets, HPS Light

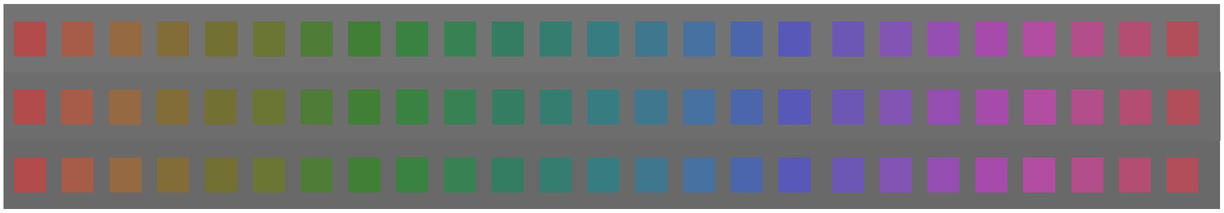

Figure A10. Chromatic Targets, White Light, Reduced Luminance

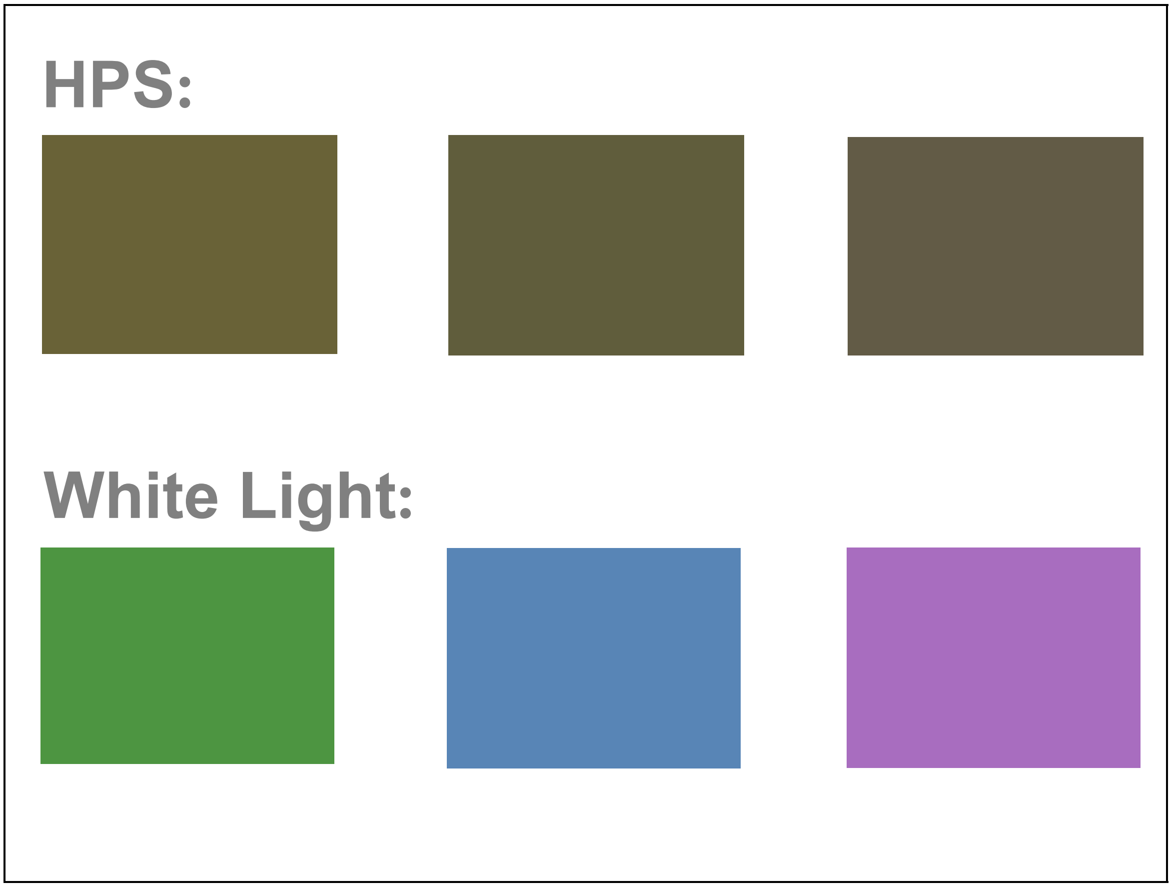

Figure A11. Color rendering demonstration, HPS, and White Light

APPENDIX B

Technical Report

IN-SERVICE LIGHTING PERFORMANCE RELATED TO ROADWAY SAFETY

Reference: Research Topic SPR 522-2

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April 2003

APPENDIX B

IN-SERVICE LIGHTING PERFORMANCE RELATED TO ROADWAY SAFETY

B1. INTRODUCTION

In the 1960's, high pressure sodium lamps (HPS), began to supersede mercury systems. They offered the advantages of high luminous efficacy, long life, compactness and good lumen depreciation characteristics. HPS has improved further since that time, with the early problems of premature failure being largely overcome. HPS has become by far the most widely used lamp for new roadway lighting installations.

Considerably prior to the introduction of HPS, the low pressure sodium lamp (LPS) had been in use. Although never widely used in the USA, this source has been of great importance, particularly in Europe and South America. Its chief advantage is its exceptionally high efficacy (lumens per watt). It also possesses the highest lumen maintenance factor of any lamp type (although wattage over life may rise as a result). Two disadvantages of LPS are physical size and cost. Size is a particular disadvantage: the optical system of a luminaire requires a small source for accurate light control. As a result, the lamp is not as well suited as other sources for lighting areas which consist of narrow strips such as roadways. Utilization Factors for LPS lamps are therefore usually lower than for other sources because its output cannot be precisely directed using fixtures of a practical size.

Metal halide is the third lamp type useable for efficient roadway lighting. It is compact and can be optically controlled as well as HPS. Its lumen output is not so high as either sodium type, but is still very high. Metal halide lamps have suffered from shorter life and poorer lumen maintenance than sodium. New technologies developed over the last two years or so, however, have increased their viability for roadway lighting through extended life and improved lumen maintenance.

An additional factor to be considered is lamp color. LPS is monochromatic yellow, while HPS is dominantly yellow. Metal halide produces white light with possible advantages in visibility and safety.

All three sources therefore have advantages and disadvantages. Use of low pressure sodium worldwide is reducing, HPS is remaining roughly even, and metal halide is a fast growing source. LPS, however, is still retained in some areas of the USA because any light pollution it produces can be filtered out by astronomers at the telescope. This is made possible because of its monochromatic output.

This research project is intended to identify information related to the use of the three light sources. This is not a simple task because of the various interrelated factors that are involved. The purpose of the study is twofold. Firstly, it is to review technical and cost information on the three light source types, and to provide a comparison based on in-service performance, maintenance issues and life cycle costs. Secondly, a goal of the project is to review available accident data, and if possible, relate accident statistics to lamp type for roadway lighting.

The report is not intended to be all encompassing owing to the number of different variations of the lamp types available, but provides a general overview of the most important aspects of the subject.

Previous work involving lamp comparisons was performed in 1984, where the significant technical and performance features of high and low pressure sodium lamps and fixtures were compared. (Reference: Final report to Arizona Public Service, “A Comparison of Low Pressure Sodium and High Pressure Sodium Lighting” by Lighting Sciences Inc., Scottsdale, Arizona). The general conclusion of this previous project was that there are numerous complicating factors involved with the two sources, and in lighting design in general, and that rated lumen output is not a clear indicator of the energy effectiveness of a particular source. Maintenance aspects, spectral distribution and visibility were not evaluated.

B2 IN-SERVICE PERFORMANCE, MAINTENANCE ISSUES AND COSTS

B2.1 Lighting Standards

There are several basic lighting standards or documents that are relevant in this review, as follows:

- AASHTO (American Association of State Highway Transportation Officials) "An Informational Guide for Roadway Lighting 1984"
- FHWA (Federal Highway Administration) Lighting Handbook
- ADOT current lighting policy
- ANSI/IESNA (Illuminating Engineering Society of North America) RP-8-00 "American National Standard Practice for Roadway Lighting"
- CIE (International Commission on Illumination) 115-1995 "Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic"

The above represent the major efforts toward providing lighting on public thoroughfares.

ADOT is concerned with high speed roadways, including expressways and freeways, for which a comparison of levels from the three documents is shown in Table B1. These are based on luminance (candelas per square meter) since all three documents use this methodology. Table B2 provides a comparison of ANSI/IES recommendations to ADOT's current practice based on illuminance (footcandles).

TABLE B1. LUMINANCE COMPARISON FOR IESNA, AASHTO, AND CIE

Road Type		**IESNA & AASHTO**	**CIE**	**Average Luminance Cd/m^2**		**Luminance Uniformity Ave/Min**		**Lane Uniformity Max/Min**		**Veiling Luminance**	
		Pedestrian Conflict	Traffic Density							**L_VMax /L_PAve**	**TI****
IES	**CIE**			IES	CIE	IES	CIE*	IES	CIE*	IES	CIE
Freeway Class A	M1		HIGH	0.6	2.0	3.5	2.5	6	1.4	0.3	10%
	M2		MEDIUM		1.5		2.5		1.4		10%
Freeway Class B	M3		LOW	0.4	1.0	3.5	2.5	6	2.0	0.3	10%
			Traffic Control								
Expressway	M1	HIGH	POOR	1.0	2.0	3.0	2.5	5	1.4	0.3	10%
	M2	MEDIUM	GOOD	0.8		3.0	2.5	5	1.4	0.3	10%
		LOW		0.6		3.5		6		0.3	
Major Road	M2	HIGH	POOR	1.2	1.5	3.0	2.5	5	1.4	0.3	10%
	M3	MEDIUM	GOOD	0.9	1.0	3.0	2.5	5	2.0	.03	10%
		LOW		0.6		3.5		6		.03	

* CIE uses Min/Avg and Min/Max. In Table B1 these have been inverted to match IES
** Maximum Threshold Increment per CIE procedures.

CIE Lighting Class:

M1 – Freeway - With high traffic density	M1 – Expressway - With poor traffic control
M2 – Freeway - With less traffic density	M2 – Expressway - With good traffic control
M3 – Freeway - With low traffic density	M2 – Major route - With poor traffic control

TABLE B2. ILLUMINANCE COMPARISON FOR IESNA AND ADOT

Road Type	**Pedestrian Conflict**	**Average Illuminance Footcandles**	
IESNA & AASHTO	IESNA & AASHTO	IES	ADOT
Freeway Class A		0.9	0.8
Freeway Class B		0.6	0.6
Expressway	HIGH	1.4	1.4
	MEDIUM	1.2	1.2
	LOW	0.9	0.9
Major Road	HIGH	1.7	1.7
	MEDIUM	1.3	1.3
	LOW	0.9	0.9

Notes: 1. IES recommendations in this table are based on R3 pavement, worn blacktop.
2. Present ADOT guidelines do not refer to lighting levels. Values are based on current practice and former guidelines.

TABLE B3. SUMMARY OF LAMP CHARACTERISTICS

Feature	HPS	LPS	MH
Size	Small	Large	Small
Optical Control	Very Good	Poor	Very Good
Life	Excellent	Good	Good
Fixture Cost	Low	High	Low
Lamp Cost	Low	High	Moderate

B2.2 Lamp Types and Data

This report will consider three primary contemporary sources:

- High pressure sodium
- Low pressure sodium
- Metal halide, pulse start type

There are a number of factors that must be taken into account before one can analyze the types of lamp/fixture combination that ADOT can consider for use in its road program. The lamp selection is a primary consideration as it influences all other design parameters. All three lamp types have advantages and disadvantages, each of which may have greater or lesser importance depending on the purpose and circumstances of the lighting design. Different lamp types may be logically selected for different applications. The following sections discuss lamp characteristics, which are also summarized in Table B3.

B2.2.1 High Pressure Sodium

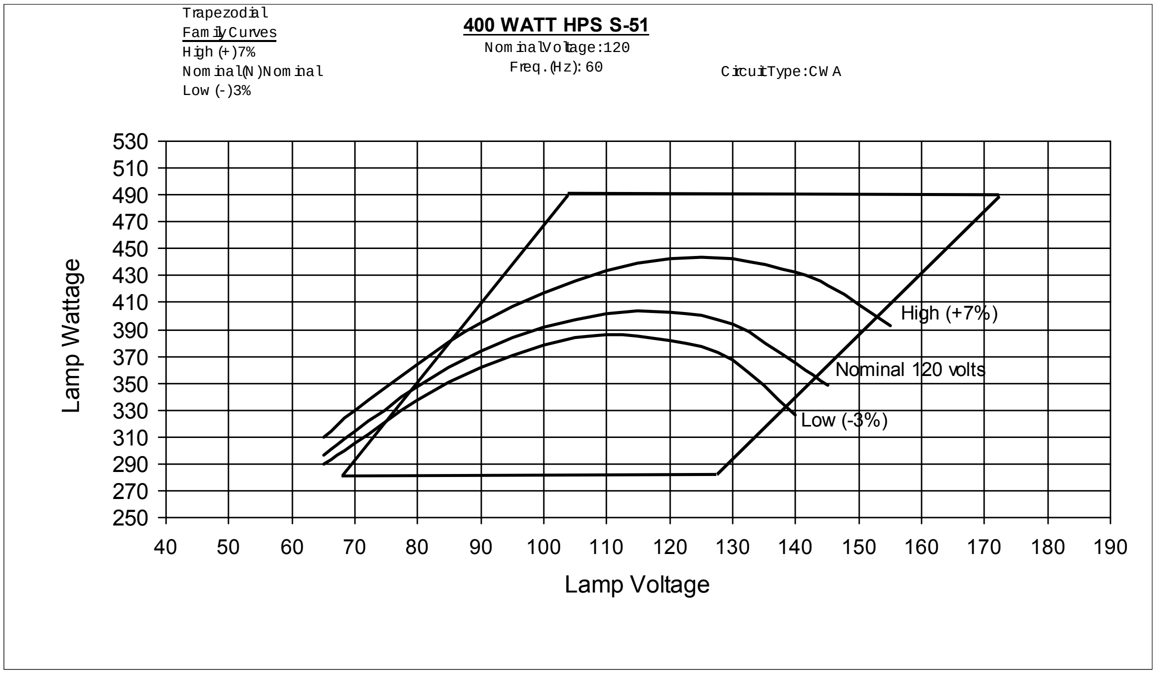

Figure B1. Lamp Voltage vs. Lamp Wattage Over Life for a 400 Watt High Pressure Sodium Lamp on a CWA Ballast. The Three Curves Shown are for +7%, -3% and Nominal Line Voltage Variation.

High Pressure Sodium is a proven and reliable light source and has excellent maintenance performance over a long life of 24,000 plus hours. The extensive use of this lamp as shown in survey results can decrease the lamp cost below $7.00 for sizes 400 watts down to 100 watts, when purchased in very large quantities.

Currently high pressure sodium is the most widely used roadway light source in the U.S. and probably overseas as well. The advantages for high pressure sodium are the high luminous efficacy, relatively small size of the source (easier to control optically), simple maintenance, very long life, low fixture cost and low lamp cost. The problems are that light output varies over life as the arc tube ages and its voltage rises; the lamp will start out at less than nominal wattage, then it will exceed the nominal wattage for a period and finally go below nominal wattage (see Fig. B1). The mean wattage over life is higher than the nominal wattage by roughly 1%. As it reaches end of life, the lamp will cycle on and off. Color rendition is better than low pressure sodium, but still quite poor in revealing green and blue.

High Pressure Sodium lamps are available in a twin-tube variety, where two parallel arc tubes are contained in the bulb. Only one arc tube is lighted, and upon its failure, the second arc tube ignites. This redundancy may potentially increase the life of the lamp to 48,000 hours, but the actual increase obtained in-service is not well-known at present. While this doubles the interval between lamp replacements, there are two disadvantages. Firstly, neither arc tube is centered within the lamp. Because of the precise nature of the optical system, this offset can cause a significant change in the fixture's photometric characteristics. This can result in a shifting of the beams, causing a dark area on the roadway. Evaluation is needed to determine whether uniformity requirements can be met with this style of lamp.

Secondly, fixture maintenance is important to keep the luminaires clean. A twin-tube lamp may last for roughly eight years, but this should not be used as an excuse for not performing maintenance for that period. For the lighting system to perform to design specifications, the maintenance interval must not be arbitrarily increased, otherwise serious deterioration of lighting performance will result.

B2.2.2 Low Pressure Sodium

Low pressure sodium lamps have been widely used overseas. They have the highest efficacy of all lamp types (based on the $V(\lambda)$ photopic curve), 183.3 lumens per watt for the 180 watt lamp. Some low pressure sodium lamps maintain their light output over life extremely well, but with an accompanying rise in power consumed of roughly 4%.

Because of the large size of the lamp, optical control is generally poor if the task of the luminaire is to direct light onto the roadway from a location on the side of the roadway. Much light spillage is likely to occur, reducing the useful lumens falling on the roadway. However, this may be an advantage in providing good visibility of the sidewalk, pedestrians and any possible incursion onto the roadway. Light trespass issues must be considered in particular with this light source.

The main concern with the low- pressure sodium lamps is the yellow color, although public reaction to this lamp from a color standpoint has been mixed. Some have indicated that the lamp color is a sunny look, giving the feeling of warmth. The fixtures are large, around 3 to 4 feet for the higher lamp wattages. Large long fixtures, due to wind pressure, place increased loads on the support structure. Certain aerodynamic shapes will lift in the wind causing vibration. Because of fixture size, this problem tends to be more serious with LPS than HPS or MH.

Fixture types for low pressure sodium lamps are limited in availability. However, several manufacturers produce roadway lighting luminaires that may be used in place of IESNA Type II or Type III cobra-head luminaires. Special photometric distributions that are available with HPS and MH, such as high mast and off highway luminaires, are not available with the LPS source.

LPS is required or encouraged for roadway lighting in some Arizona jurisdictions, some with and some without nearby astronomical facilities. (Coconino County; Flagstaff; Yavapai County; Pima County; Tucson). This is primarily as a result of efforts by astronomers.

B2.2.3 Metal Halide

Metal halide lamps were introduced in the mid-1960's. They were derived from the mercury lamp, which at that time was the dominant source for roadway lighting. The metal halide lamp is basically a mercury lamp with a variety of metal halide salts added in the discharge tube. These salts produce light efficiently, giving an increase in lumens per watt of roughly 50% over mercury lamps. Each salt emits a different color of light when excited in a vapor state; by altering the proportional mix of the various salts, different lamp SPD's can be produced. The most widely used MH sources have a salt mixture that produces white light.

MH sources have long suffered from poor lumen maintenance and short life. Older type MH sources were poor in these regards, and further suffered from inconsistent color lamp to lamp.

With the introduction roughly two years ago of the pulse start family of metal halide lamps, this source has more stable operation, and life has been improved. Life has been increased from 10,000 hrs. to 15,000 hrs. for 400 watt horizontal operation. Manufacturers anticipate this will be raised to 20,000 hours in the near future. 400 watt vertically operated lamps, base up or base down, achieve 20,000 hrs. average life. (Life is defined as when 50% of lamps are burned out, per the normal practice of lamp manufacturers). The lamp size is about the same as high pressure sodium and therefore fixtures are of a similar size.

Virtually all field experience with metal halide lamps has been with the probe-start lamps that are being rapidly superseded with pulse start lamps for new installations. Field data for metal halide sources therefore is not a reliable indicator of the performance that may be expected for future installations, and more field data therefore are needed. It takes years to verify life expectancy even with accelerated tests, and laboratory tests do not always duplicate field experience. Manufacturers claim substantial improvements in lumen maintenance characteristics with pulse start lamps, but this is another factor that requires investigation.

Further improvements have been obtained in lumen maintenance by use of the now available pulse start electronic ballasts. These ballasts reduce ballast power losses versus magnetic ballasts, and operate the lamp at constant wattage through life.

Presently the development of metal halide lamps has concentrated on vertical burning lamps, although horizontal burning pulse start lamps have recently become available. Normally the lumen output of vertical burning lamps exceeds that of horizontal burning lamps by about 10 percent. This is a disadvantage in roadway applications if the fixtures use horizontal lamps, but suggests that luminaires using vertical burning lamps should be considered for future metal halide installations. Vertical burning lamps, however, are common in interchange high mast lighting and the freeway "off-highway" system.

Metal halide lamps are available with two different classes of arc tube. Quartz arc tubes have been used universally in the past, but a new range of lamps with ceramic arc tubes has recently been introduced by several manufacturers. Ceramic arc tube lamps are not readily available in large wattages, and presently are therefore limited in roadway lighting applications. As lamp performance for the two different types of arc tube is different, data is presented in this report for both.

Generally developments in both high pressure and low pressure sodium lamps have been fairly well stabilized; new wattages tend to follow proven design techniques. Given the proper amount of time, the metal halide lamps may be a good economical choice as well.

A summary of lamp life and lumen output is shown in Tables B4a and B4b.

B2.2.4 Lamp Disposal

Lamp disposal is of increasing concern due to environmental considerations. Of the three sources, MH contains the highest mercury content. LPS is capable of creating fire if carelessly discarded. For all lamp types, proper disposal is essential; lamp recycling is to be preferred and facilities for this are now available.

B2.2.5 Other Considerations

The low pressure sodium (LPS) light source is a product that was developed on a very narrow interpretation of the CIE $V(\lambda)$ photopic curve. The foundation of LPS, and for that matter to a lesser extent also high pressure sodium (HPS), as the most "efficient" light sources (as measured in lumens per watt) is based on the assumption that the eye's peak sensitivity is to yellow light. Thus, both LPS and HPS light sources were designed to produce lots of yellow light, which in turn gives them the most lumens per watt because the CIE photopic curve gives the most credit for lumens produced in the yellow light spectral range. Thus, these light sources have been designed with little consideration to anything else. Therefore, if CIE response curve is changed to give more credit for lumens for light in other areas (e.g. scotopic function) these two light sources will be rated very differently. Appendix A gives detailed discussion of these point.

It is well recognized that we do not see by yellow light alone! We see based on light and color. Color is produced by seeing under light sources (such as the sun) that produce visible light in a combinations of colors, not just light of one color. Therefore, a good lighting design is one that gives balanced consideration to not only the physical and efficiency aspects of the lighting system (e.g. lumens per watt, pole spacing, light pollution, glare, etc.), but also to how people will see in that system (e.g. seeing environment). Further analysis is provided in Appendix A.

A good seeing environment promotes better function performance which in turn (for roadway lighting) should lead to safer driving. The lighting design metric historically used, illuminance, does not address visibility directly. Instead, it uses criteria like "average", "minimum" and "average to minimum" to try and define what a lighting system needs to be for seeing. Attempts have been made to try and develop better metrics, such as luminance and small target visibility (STV). However, these metrics still do not define actual visibility in terms of how a human eye really sees.

A LPS lighting system does not give balanced consideration on how a human eye actually sees. A HPS lighting system, like those that ADOT typically uses, does not fully do this either. High pressure sodium (HPS) does have some spectral power in other light colors, which allows some colors to be seen. On the other hand, LPS is a monochromatic source which only emits yellow light. Therefore, everything that is seen under this source either looks yellow or a shade of gray. Thus, drivers can not see important colors such as red, white and green under a lighting system such as this. MH on the other hand does render all of the basic highway colors fairly well. Thus, it terms of providing similar color rendering, as compared to daylight, MH does a very good job as compared to HPS and certainly LPS. In a strict interpretation of the 2000 MUTCD Section 2A.08 Retroreflectivity and Illumination (page 2A-5), LPS does not render colors well enough to meet this standard for all signs, except yellow warning signs and yellow pavement markings. HPS is also different. MH, on the other hand, renders colors properly.

LPS, or for that matter, any light source which has poor "far away" optical control characteristics (e.g. fluorescent), requires that poles be placed closer to the roadway than good "far away" optical control type sources like HPS and MH. Having poles closer to the roadway is just as important to safety as the pole spacing. Because of fixture photometrics, a large pole set-back from the curb is not achievable with LPS. On the other hand, HPS and MH fixtures are able to throw the light out farther, and this in turn allows poles to be offset further, in some cases (when you use the offset fixtures like the Holophane/ITT Expressway/Interstate or GE Expressway) to exceed the clear zone distances as defined in the AASTHO Roadway Design Guide. This is clearly an advantage for HPS and MH systems, if a safe lighting design is defined as a system that allows the fewest number of poles that are spaced out as far as possible and are as far away from the roadway as possible. Using slip-away/break-away type of poles does not necessary mitigate hazards that are within the clear zone. It is almost always safer not to have poles in the clear-zone.

However, for roadways that do not have clear-zone issues, LPS starts to match up better with HPS and MH. Typically, these are roadways with speed limits 45 mph or less (arterials, minor arterials, collector and minor streets).

LPS is also limited in available wattages, with 180 watts being the maximum customarily used. Thus, in terms of lighting multiple lane freeways limits its usefulness. Typically, 400 watt HPS fixtures with 50,000 lumens are used for freeway to freeway interchanges and for really wide roadways such as urban portions of I-10 (which is 110' feet wide).

LPS lamps were developed in the 1940's and have changed little since. HPS lamps were first produced in the mid-1960's and have become more efficacious and reliable over time. However, little performance improvement has occurred in recent years, although a double arc tube HPS lamp has been introduced fairly recently. MH lamps were also developed in the mid-1960's and for many years suffered from lamp-to-lamp variations, short life and poor lumen maintenance. Because of this, they developed a bad reputation. Their performance over the last few years however has improved dramatically, particularly with the introduction of the pulse-start family of lamps. While their performance does not yet match HPS, if current trends continue it can be anticipated that they will equal HPS within a few years.

B2.3 Design Aspects

A fundamental factor in the designer's choice of lamp type is the lamp lumen output, and its efficacy (lumen per watt). Care must be exercised in this regard. Manufacturers tend to emphasize "rated lumens." These are the lumens produced by a typical lamp after 100 hours of burning, and often called "initial lumens."

A roadway lighting system is required to meet specifications not only when the lamps are new, however, but all through the time period that the lamp is in use. If a lamp is changed only when it burns out, it is the end of life lumen output that is significant. If lamps are changed after a time period where it is estimated that they have reached, for example, 80% of their rated life, it is the "80% life lumens" that must be used by the designer. ("Rated life" is the point at which 50% of the lamps can be expected to have failed. Manufacturers use a 40% of life figure for metal halide lamps).

This report provides data on initial, average through life, 80% life and end-of-life lumens. Initial and average-through-life (or mean) lumens have no particular significance to the designer.

The factor that relates the lumens under a particular condition to the initial lumens is referred to as the lamp lumen depreciation factor, LLD. If the LLD is 0.80 for 80% life, this indicates that the lumen output of the lamp will have fallen by 20% from its initial value when the lamp has reached 80% of its rated life. LLD values can be obtained from manufacturers' data.

Luminaire lumen output will reduce by more than that of the lamp itself as a result of dirt accumulation. Dirt depreciation in a state such as Arizona is estimated at 10% maximum, assuming regular cleaning intervals of approximately two years. This value may be substantially greater if maintenance is not conducted regularly. The combined reduction due to lamp lumen depreciation and luminaire dirt depreciation is referred to as the Light Loss Factor, LLF, sometime referred to as the Maintenance Factor. Data based on lumen values adjusted to represent realistic conditions by use of Light Loss Factors is referred to as "in-service data."

Tables B4a and B4b give information for the three sources related to lumen output under various conditions.

The designer of road lighting must always begin with maintenance in mind. Once the road category is determined, the level is selected for the particular road, and the lamp type is chosen. The designer then must determine the maintenance factor. This is usually available from lamp manufacturers and/or the Illuminating Engineering Society of North America. Tables B4a and B4b and Figure 2 give information on lamp lumen output over time for the commonly used higher wattage lamps.

TABLE B4a. SODIUM LAMP DATA

High Pressure Sodium			Low Pressure Sodium
Wattage	400	250	180
Burning Position	Universal	Universal	Hor. ± 20°
Initial Lumens	51,000	28,000	33, 000
Mean Lumens	45,000	27,000	33, 000
80% of Life Lumens	43,350	33,000	30,000
End of Life Lumens	41,820	22,960	33,000
Hours Life	24,000+	24,000+	18,000
Initial System Wattage	464	295	220

Note: System wattage based on a CWA (Constant Wattage Autotransformer) type ballast.

TABLE B4b. METAL HALIDE LAMP DATA

	Metal Halide Quartz Arc Tube				**Metal Halide Ceramic Arc Tube**	
WATTAGE	400	400	250	250	250	150
Burning Position	VERT.	HORIZ .	VERT.	HORIZ.	VERT.	VERT.
Initial Lumens	44,000	40,000	25,000	22,500	24,000	14, 000
Mean Lumens	37,400	32,800	20,000	18,000	19,200	11,200
80% of Life Lumens	34,100	30,000	20,250	16,875	Unknown	Unknown
End of Life Lumens	33,000	29,000	16,750	15,075	14,880	8,680
Hours Life	20,000	15,000	15,000	11,250	15,000	15,000
System Wattage	421	421	295	295	295	189

Note: System wattage based on electronic ballast. Wattage is constant throughout life.

Note: System wattage based on a pulse start electronic ballast, and standard pulse start ballast for other types.

High pressure sodium and low pressure sodium performance have been very stable over the past few years in lumen output, wattage, size, depreciation etc. There have been a few minor changes at most. Metal halide lamps, however, have been in a situation of rapid change, with improvements in lumen output, lumen maintenance, wattage range, color and types. With the advent of pulse start (using an ignitor as a starter) and ceramic arc tubes, various manufacturers have been making new sets of lamp families. There are now a variety of lamps at 200 watts, 250 watts, 300 watts, 320 watts, 350 watts, 400 watts and 450 watts. Many and varied smaller sizes are available as well.

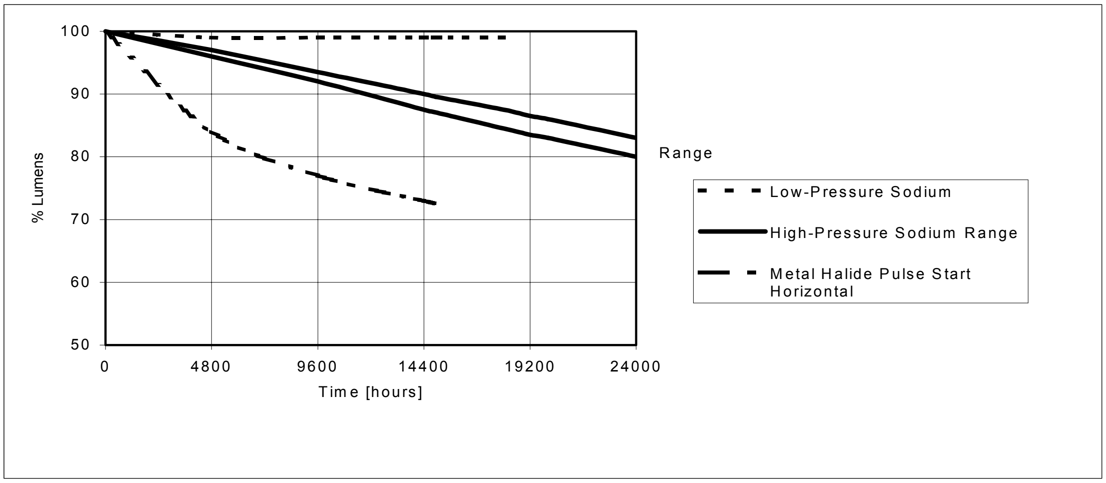

Figure B2. Lumen Maintenance Over Life for Three Sources. Low Pressure Sodium, High Pressure Sodium (with CWA ballast) and Pulse Start Metal Halide (with electronic ballast). Curves are shown to end of rate life.

There are also the high pressure sodium replacements or retrofit type of metal halide lamps. If all variables are considered, there are more than 400 metal halide lamp types on the market and still the number is growing.

This report includes the 250 watt and 400 watt pulse start metal halide lamps with quartz arc tube and with ceramic arc tube, to give an overall comparison with high- pressure and low pressure sodium.

B2.4 Lamp Orientation

A further factor that requires attention is lamp orientation. Some fixtures utilize a horizontal burning lamp while others use a vertical lamp. Most roadway lighting fixtures use a horizontal lamp, but vertical or near-vertical burning is employed in the off-highway, or set back, lighting system used widely by ADOT for freeway lighting. Vertical lamp fixtures are also used for high mast interchange lighting.

All three lamp types can be operated either vertically or horizontally. The sodium sources do not change significantly in their performance depending on orientation. Metal halide sources, however, perform best when burning vertically. When operated horizontally, lumen output and lumen depreciation worsen and life is shortened. However, these problems are lessened as a result of the recently introduced pulse-start lamps that are optimized for horizontal operation.

Any disadvantage of metal halide lamps with regard to orientation, of course, does not occur with the off-highway or high mast fixture types.

Lamp orientation effects the fixture's photometric distribution. Horizontal lamps offer advantages in generating high candlepower that can be aimed down a roadway to fill in dark areas between poles. However, because of the horizontal orientation, the arc tube is presented broadside to points directly beneath the fixture. This produces high candlepower at the very worst location (because the distance from the fixture to the pavement is short). The result is a pool of excess light near each pole, which creates poor uniformity and wastes energy.

The pool of light problem is eliminated with a vertical lamp, as only the end of the arc tube is presented to points on the pavement close to the pole. Generating an intense beam that is aimed to locations between poles, however, is more difficult with a vertical lamp. It is particularly difficult with high wattage HPS because of its fairly long arc tube, and essentially impossible with LPS.

The widespread use of horizontal lamp fixtures for roadway applications is partially due to the fact that HPS is equally efficient both horizontally and vertically. If MH usage for roadway lighting becomes significant, we can expect fixture manufacturers to offer roadway luminaires using vertical MH lamps to harness their improved performance versus horizontal operation.

B2.5 Life

Lamps rated at many thousands of hours life have usually been laboratory tested with accelerated schedules such that hours of life data may be published relatively shortly after the lamps are introduced for sale. These lamps have not necessarily been subjected to field conditions where extreme weather, vibration, handling, positioning, insertion, corrosive or polluted atmospheric conditions prevail.

Maintenance contractors who are responsible for replacing individual outages as part of their routine contract have often complained that burn out rates exceed those predicted by the published data. They have asked that group relamping on high pressure sodium lamps be changed from a four (4) year 16,000-hour cycle to a three (3) year 10,000-hour cycle. In fact, in-service lifetime issues have been raised for all lamp types.

Published information is now stating that these high pressure sodium lamps will on average last 24,000 + hours. See Table B4a and B4b for life hours. This should decrease the burn out rate, but caution is recommended. Twin–tube lamps may double this figure, see earlier section. Pulse start metal halide lamps are relatively new technology, and as such limited field experience is available. Manufacturers' lifetime data therefore may be uncertain.

B2.6 Failure Mode

A recent problem with high pressure sodium lamps (that in all probability could occur with any similarly constructed lamp) is the failure of arc tube connector welds. Welding connections are extremely important as broken welds where metal to metal contact is intermittent can create pulses which may destroy the ballast. A recent occurrence in one city where new lamps were installed as part of a relamping program resulted in the destruction of many existing ballasts.

Lamp cycling has also been a problem in maintenance. High pressure sodium lamp voltage rises over life until the ballast is unable to sustain the arc voltage. The lamp extinguishes, cools down, restarts and burns until the voltage rise causes the lamp to extinguish. If patrolling is the means for detecting lamp outages, the patroller may see the lamp lit as he passes by and miss the outage. The same experience may occur where police and other agencies are responsible for notification of outages. Non-cycling lamps and devices are available to prevent this phenomenon.

Modern metal halide sources may also exhibit end of life cycling. For pulse start lamps, about 25% show this characteristic. In addition, about 10% of MH lamps experience rupturing and possible explosion at end of life. This can be eliminated by special construction available in some lamp types, but such rupturing is not regarded as a problem if enclosed fixtures are used.

B2.7 Economic Considerations

The cost of lamps and fixtures is difficult to predict as it is highly dependent on quantity, type of bid, competition, and other factors such as installation being required or provision of storage etc. List prices for individual lamps are of course very high compared to volume purchases, but the following prices may give a reasonable ratio between different lamps and different sizes:

TABLE B5. LAMP COST DATA

Lamp Type	Wattage	Lamp Price
High Pressure Sodium	400	$26
High Pressure Sodium	250	$26
Pulse Start Metal Halide Quartz Arc Tube	400	$59
Pulse Start Metal Halide Quartz Arc Tube	250	$58
Pulse Start Metal Halide Ceramic Arc Tube	250	$89
Low Pressure Sodium	180	$80

Currently the price of metal halide lamps is from 2.3 to 3.5 times that of high pressure sodium. It is anticipated that this high cost of metal halide lamps will come down in relation to high pressure sodium as production volume increases and other manufacturing improvements are made. No significant change is expected in the cost of low pressure or high pressure sodium, apart from inflation.

Assuming lamps and photo-controls are provided separately, the fixture cost should only differ by the cost of the ballast. Many fixtures have been designed to allow either high pressure sodium or metal halide lamps with minor adjustments. However, photometric performances due to differences in lamp characteristics will occur and will affect the number of luminaires required for a given lighting level. This must be carefully considered in the design of lighting systems.

Fixture prices as quoted to distributors are as follows:

TABLE B6. FIXTURE COST DATA

Lamp Type	Fixture type	Wattage	Fixture price
High Pressure Sodium	Ovate	400	$312
High Pressure Sodium	Ovate	250	$307
Metal Halide Pulse Start	Ovate	400	$342
Metal Halide Pulse Start	Ovate	250	$337
Low Pressure Sodium	Rectangular	180	$697

These prices are all subject to various discounts and actual costs can be as low as one-third of the above. Relatively speaking, the cost of the luminaire (fixture plus lamp) is small compared to the total installation cost of the pole, mast arm, wiring and connection to power source.

B2.8 Energy

A comparison of the three light sources relative to system wattage indicates that low pressure sodium is the most efficient source in generating lumens in the photopic region of the spectrum. High pressure sodium is second highest and pulse start metal halide is third.

Table B4 makes interesting comparisons of both mean lumens per watt and initial lumens per watt. Since conservation of energy has become increasingly important as well as the cost of energy over a long period, consideration of the most efficient sources is prudent. The total energy consumed, however, depends on the energy efficiency plus the geometric layout, and of course, the number of fixtures required per mile of roadway is highly important. Lighting systems are designed to meet specifications at the end of lamp life. Therefore they must initially be overdesigned such that they will not fail to meet the required performance after lumen depreciation has occurred. The closer the design lumens are to the initial lumens, the less overdesign is needed.

The data provided in Table B7 takes into account ballast losses, which are generally highest for low pressure sodium and lowest for metal halide. Also taken into account is the wattage increase over life with sodium lamps.

TABLE B7. SYSTEM WATTAGE OVER LIFE

Lamp Type	High Pressure Sodium		Low Pressure Sodium		Metal Halide Pulse Start Vertical		Metal Halide Pulse Start Horizontal	
Nominal Lamp Wattage	400	250	180	135	400	250	400	250
Initial System* Wattage	464	295	220	178	421	295	421	295
End of Life System Wattage	475	305	232	221	421	295	421	295
Average System Wattage	470	300	229	205	421	295	421	295
System Mean Lumens per watt over life**	95.7	90	144	109.8	88.8	67.8	77.9	61.0

* Lamp power plus ballast losses

** Computed from mean lumens over life and average system wattage over life.

See Table B4 for lumen data

Metal Halide data is based electronic ballast use.

B2.9 Color

Table B8 is a rating sheet of how well colors appear when illuminated under various sources. The colors are representative of those used on traffic control and directional signs, but also relate to typical vehicle colors and colors of pedestrian clothing. The information is extracted from IESNA publication RP-19, Recommended Practice for Highway Sign Lighting.

Many engineers feel that the ability to render color in the scene at night is of considerable importance, as color enhances visibility and therefore can be expected to contribute to safety. On this topic, the Manual on Uniform Traffic Control Devices [22] states "Regulatory, warning, and guide signs shall be retroreflective or illuminated to show the same shape and similar color by both day and nigh, unless specifically stated otherwise in the text discussion in this Manual of a particular sign or group of signs." However, the importance of color rendition provided by a fixed lighting system in the presence of automobile headlamps is uncertain.

TABLE B8. COLOR RENDERING

OBJECT COLOR	METAL HALIDE	HIGH PRESSURE SODIUM	LOW PRESSURE SODIUM
Blue	Excellent	Poor	Very poor
Green	Excellent	Poor	Very poor
Yellow	Good	Good	Good
Orange	Good	Good	Good
Red	Good	Fair	Very poor
Brown	Good	Poor	Poor
White	Excellent	Fair	Very poor

B2.10 Summary

No overall conclusion can be drawn regarding the selection and suitability of a particular lamp type for a certain roadway lighting design. Each source has its own advantages and disadvantages, and the optimum lamp type for a given situation will be dependent on many factors and their relative importance in relation to local circumstances.

B3. HYPOTHETICAL ROADWAY LIGHTING DESIGNS AND COST ANALYSIS

B3.1 Purpose and Method

Part of the research work has been the development of three lighting designs, one for each of the three source types, for an identical section of roadway. These are based on in-service values and thus take into account lumen maintenance. Cost estimates then have been made as a further basis for comparing the three systems.

Per discussions with the Technical Advisory Committee, the following roadway characteristics were assumed for the designs:

- Three lane roadway
- Lane width = 12 feet, 4 feet shoulders on each side
- Pole location = 8 feet setback from edge of shoulder
- Lighting levels per ANSI/IESNA assuming a major road classification with low pedestrian activity, R3 pavement classification.
- In-service lumens based on 80% of lamp life condition

The design criteria, per IESNA, were at least 0.90 footcandles maintained, an average-to-minimum illuminance ratio of 3.0:1 or better, and glare limitation of 0.30, (ratio of maximum veiling luminance to average pavement luminance).

The designs were conducted to maximize pole spacings while meeting the specifications. The following were varied as part of the optimization procedure:

- Pole arrangement, one sided or staggered
- Lamp wattage
- Mounting height, 35 to 45 feet range
- Mast arm length, 2 to 13 feet (measured from pole center to luminaire center)
- Luminaire type, but all flat glass cut-off fixtures

Initial designs investigated one-sided versus staggered poles. A staggered arrangement in most cases gave very slightly better performance. In view of the minor nature of the improvement, however, one sided systems were used as the basis for comparison because of increased cabling costs for staggered systems.

Designs were conducted for various lamp wattages, up to 450 watts. Pole spacings were found to be greatest using the highest wattages in the range for all three lamp types. This dictated the use of 400 watt HPS lamps, 180 watt LPS lamps, and 400 watt MH lamps.

B3.2 Design Results

B3.2.1 High Pressure Sodium

Table B9 provides details of the optimized system for HPS. Luminaire photometric performance was obtained from General Electric Company, while lamp data were obtained from Philips.

At a spacing of 276 feet, the HPS lamp requires the minimum number of poles per mile of the three sources.

TABLE B9. OPTIMIZED DESIGN RESULTS FOR HPS

Luminaire type	General Electric M400A Power/Door® with cutoff optics. Type II cutoff fixture with flat glass. Catalog #MDCL40SXXXXXXFMC2XXX.
Pole arrangement	One Side
Mounting height	45.0 ft.
Mast arm length	5.0 ft.
Lamp type	400 watt
Lamp rated life	24000 hrs
Lamp lumen output (80% of life)	43,350 lms
Luminaire dirt depreciation factor	0.78
Optimized pole spacing	276 ft.
Design results:	
Average illuminance	0.91 fc
Ave/Min uniformity	3.0 : 1
Glare ratio	0.30 : 1
Limiting Criteria	Uniformity and Glare Ratio

B3.2.2 Low Pressure Sodium

Table B10 provides details of the optimized system for LPS. Luminaire photometric data was supplied by Gardo, while lamp data were obtained from Philips.

TABLE B10. OPTIMIZED DESIGN RESULTS FOR LPS

Luminaire type	Gardo Form 10. Type III full cutoff fixture with flat glass. Catalog #LA141S180LPSXXXXXXXX.
Pole arrangement	One Side
Mounting height	39.75 ft.
Mast arm length	12.0 ft.
Lamp type	180 watt
Lamp rated life	18000 hrs
Lamp lumen output (80% of life)	33,000 lms
Luminaire dirt depreciation factor	0.84
Optimized pole spacing	176 ft.
Design results:	
Average illuminance	0.90 fc
Ave/Min uniformity	3.0 : 1
Glare ratio	0.16 : 1
Limiting Criteria	Illuminance and Uniformity

At a spacing of 176 feet, the LPS lamp requires the largest number of poles per mile of the three sources. 56.8% more poles are required versus HPS.

B3.2.3 Metal Halide

Table B11 provides details of the optimized system for MH. Luminaire photometric performance was obtained from Cooper, while lamp data were obtained from Holophane and Venture Lighting.

TABLE B11. OPTIMIZED DESIGN RESULTS FOR MH

Luminaire type	Cooper Streetworks OVF/flat glass luminaire. Type II full cutoff fixture with flat glass. Catalog #OVF40MXX2D.
Pole arrangement	One Side
Mounting height	42.0 ft.
Mast arm length	12.0 ft.
Lamp type	400 watt
Lamp rated life	15000 hrs
Lamp lumen output (80% of life)	30,000 lms
Luminaire dirt depreciation factor	0.86
Optimized pole spacing	246 ft.
Design results:	
Average illuminance	0.90 fc
Ave/Min uniformity	3.0 : 1
Glare ratio	0.29 : 1
Limiting Criteria	Uniformity

At a spacing of 254 feet, the metal halide system requires 8.7% more poles per mile versus HPS.

B3.3 Cost Comparison

The cost comparison must be based on initial capital costs and operating costs. Total ownership costs can be calculated if desired by amortizing the initial costs over a selected time period.

Table B12 provides a summary of all cost calculations.

B3.3.1 Initial costs

Highway lighting construction costs have been obtained for the job costing document TRACS No. 264 AP 471 H3905 01C, covering the lighting of State Route 264 from the Navajo Forest Boundary to the New Mexico State line. This is based on the use of 400 watt HPS luminaires. Costs have been broken down into fixed costs per mile, primarily electrical distribution, that do not vary with pole spacing, and total costs per mile. From this, the cost per luminaire location is determined.

Fixed cost per mile = $55,000
Cost per luminaire location = $3225

The cost per luminaire location can be used as a base case for HPS, applicable to any pole spacing.

The cost per location for the other sources can be based on the HPS cost per location, plus the difference in cost of each lamp and fixture. Lamp costs provided in section 2.7 have been discounted by 50% to be representative of actual costs to ADOT.

Total system initial cost per mile is obtained by adding the fixed cost per mile to (cost per location x number of poles per mile):

$$\text{System cost/mile} = \left[\frac{5280}{\text{spacing}} \times \ \text{cost per location}\right] + \text{fixed cost/mile}$$

Values for the three lamp types are provided in Table B12.

B3.3.2 Power Costs

Power costs per mile, based on the average fixture power over the life of the lamp, are calculated from:

$$\text{Annual Power Costs/Mile} = \frac{5280}{\text{Pole spacing}} \text{ x Avg. fixture power x \$ per KWH x burning hrs/yr.}$$

Average fixture power, including ballast losses are:

HPS	470 watts
LPS	229 watts
MH	421 watts

An example electricity cost of $0.08/KWH has been used, and an average of 12 burning hours per day has been assumed.

Values for the three lamp types are provided in Table 12.

B3.3.3 Maintenance Costs

Maintenance costs are highly dependent on the form of maintenance. For example, group relamping at a preset interval will increase maintenance efficiency and reduce labor cost but is likely to increase lamp costs, when compared to spot relamping.

For this analysis, it has been assumed that the systems will be group relamped, and that this will occur at 80% of rated lamp life. Cleaning will also occur at that time only. These intervals will vary by lamp type.

For an average annual burning hours of 365 x 12 = 4380 hours, the lamp change intervals will be:

$$\text{Lamp Change Interval} = 0.8 \times \frac{\text{Rated Life}}{4380}$$

The values for the three sources are:

Lamp Change Interval, HPS = 4.4 years
Lamp Change Interval, LPS = 3.3 years
Lamp Change Interval, MH = 2.7 years

It has been assumed that a maintenance visit costs $10 in labor. On this basis the maintenance costs per year are:

$$\text{Maintenance Cost per Year per Mile} = \frac{10 + \text{Lamp Cost}}{\text{Lamp Change Interval}} \times \frac{5280}{\text{Pole Spacing}}$$

Values for the three lamp types are provided in Table B12.

B3.3.4 Total Operating Costs

It will be recognized that the above cost figures can vary considerably from the examples provided above. However, to the extent that these figure are applicable, the total operating costs can be found by summing the power and maintenance costs, which are provided in Table B12.

Note that the figures in Table B12 are calculated for horizontal burning 400 watt metal halide lamps. For fixtures using vertical burning lamps such as the expressway luminaire used widely by ADOT, lamp rated life increases from 15,000 hours to 20,000 hours. Lumen output also increases, but if pole spacing were to remain as calculated above, maintenance costs will be reduced by 25%.

B3.3.5 Payback Period

LPS has a higher initial cost than HPS, but lower operating costs. Ignoring financial factors such as opportunity rates, cost of capital and inflation, and simply developing payback from annual cost savings, the payback period for LPS can be calculated. This is provided in Table B12.

No payback period exists for MH versus HPS, as both MH's capital cost per mile and its annual operating costs are higher than for HPS.

B3.3.6 Total Capital and Operating Costs

Capital and Operating costs also can be compared over the life of the lighting system. This varies greatly with the chosen life. An example is provided in Table B12 based on a 30 year operating life. (Financial factors such as opportunity rates, cost of capital and inflation are not included).

These figures are calculated for systems which meet IESNA specifications. They do not take into account research findings that appear to support the use of a reduced level of MH versus the other sources, based on visibility increases.[21] If a small reduction in lighting level were applied to the white light source performance requirements, the MH system would decrease in its cost to below that of HPS.

B3.3.7. Cost of Accidents

Analyzing the cost of accidents is not possible as part of this study. Information is available from the National Highway Transportation Safety Administration regarding the cost per accident. However, no information is available that relates frequency and type of accidents to lamp type. Engineers generally feel that safety is improved when pole spacings are large, or when poles can be placed distant from the roadway edge, other factors being equal, as this reduces the frequency of vehicle/pole collisions.

B3.4 Light Trespass

Light trespass is of concern in many communities, and local ordinances may be in place that limit spill light. These do not generally apply to roadway lighting systems, but roadway lighting is usually designed to limit light spilled outside the primary area being lighted. Spill light represents wasted energy. Such light also will reflect from the lighted surfaces and will contribute to light pollution while providing little or no commensurate benefit. The three optimized lighting systems have been analyzed for their spill light.

Spill light lumens per mile:

HPS	430,000 lms/mile
LPS	405,000 lms/mile
MH	275,000 lms/mile

The above figures are based upon the initial lumen outputs of the luminaires, as this is the point in life when the light trespass is maximum. This is advantageous to LPS as because of its excellent lumen maintenance characteristics, the system does not require overdesigning to compensate for lumen depreciation over life.

The spill light value for HPS is surprisingly high, and this appears to be due to a combination of factors. Firstly, it uses the highest mounting height, and this in itself is likely to cause greater spillage. Secondly, it uses the widest pole spacing, and the width of the beams spreads more to the points in-between poles, and therefore a greater amount of light falls outside the roadway area. Thirdly, the arc tube of HPS is greater than that of MH, which is a major factor that limits the precision of light control. Fourthly, because of the long life of HPS, it has the poorest dirt depreciation factor, which must be overcome by initial overdesign, and the light trespass values are based on initial performance. LPS and MH both benefit from the use of a 12 ft. mast arm, which places the fixture in a preferred location with regard to reducing spill light.

TABLE B12. SYSTEM COST COMPARISON

Initial Costs	**HPS**	**LPS**	**MH**
Total costs per mile, HPS	$116,700		
Fixed costs per mile	$55,000	$55,000	$55,000
Other costs per mile, HPS	$61,700		
Pole spacing	276 feet	176 feet	246 feet
Cost per lamp	$13.00	$40.00	$29.50
Cost per luminaire	$312	$697	$342
Cost of lamp & luminaire	$325	$737	$372
Cost per location	$3,225.23	$3,637	$3,272
System cost per mile	$116,700	$164,117	$125,222
Cost vs. HPS	100.0%	140.6%	107.3%
Power Costs			
Luminaire power incl. ballast	470 watts	229 watts	421 watts
Assumed cost per KWH	$0.08	$0.08	$0.08
Assumed burning hrs/day	12 hours	12 hours	12 hours
Annual power cost per mile	$3,151	$2,407	$3,166
Power costs vs. HPS		76.4%	100.5%
Maintenance Costs			
Lamp rated life	24,000 hours	18,000 hours	15,000 hours
Lamp change interval (based on 80% life)	4.38 years	3.29 years	2.74 years
Maintenance labor per visit	$10.00	$10.00	$10.00
Maintenance cost per mile per year	$100	$456	$309
Maintenance costs vs HPS		454.5%	308.3%
Total Operating Costs			
Power & maintenance per mile per year	$3,251	$2,863	$3,476
Total operating costs vs HPS		88.1%	106.9%
Payback versus HPS			
Increase in capital cost per mile		$47,417	$8,522
Decrease in operating costs per mile		$387	-$225
Payback period		122 years	NA
Total Owning Costs			
System life	30 years	30 years	30 years
Initial costs per mile	$116,700	$164,117	$125,222
Operating costs over life, per mile	$97,528	$85,905	$104,271
Total costs over life, per mile	$214,228	$250,022	$229,493
Total life costs vs HPS		116.7%	107.1%

B4. ACCIDENT STUDIES

The relationship between accident frequency, accident types and lamp color is of great interest. Accidents that are caused by visibility problems are of a variety of types, involving foveal vision, peripheral vision or a combination of the two.[23,24] These different forms of vision are likely to be related to the types of accident that will occur if vision is inadequate. Vehicle guidance, for example, requires both foveal and peripheral vision. Reading signage is primarily a foveal task. Other forms of accident that occur when an object moves into the driver's path from the side may be attributable to a failure of peripheral vision. Because of the spectral effects that are described in Appendix A, it may be anticipated that lamp type can influence the frequency of various types of accidents.

A survey has been made by way of questionnaires and telephone contacts with all the states and three Canadian provinces (Ontario, Alberta and British Columbia). Of the states contacted, responses were received from all but Kansas and Illinois. Numerous U.S./Canadian cities also were contacted. (Rochester New York, Dallas, Fort Worth, Los Angeles, Baton Rouge, Sacramento, Glendale Arizona, Philadelphia, Milwaukee, Toronto, Portland Oregon, Seattle, San Jose, Denver, San Francisco and Tucson). Other contacts were made with 37 foreign agencies, the FHWA, AASHTO, ITE (Institution of Transportation Engineers), IESNA, EPRI (Electric Power Research Institute), CIE, and the LRC (Lighting Research Center). Also several IESNA Roadway Committee members were contacted to secure ‘leads’. The questionnaire used in the U.S./Canadian governmental contacts is given in the addendum. The foreign contacts used a similar form. Typically, the domestic questionnaires were sent to state and city traffic engineers.

The intent of the questionnaire and the direct contacts was to identify pertinent published or unpublished public agency reports and determine the types of lamps typically used on freeways, rural roads, and major (urban) streets. If any significant use of LPS or MH lamps existed, the responder was asked to identify any available reports comparing lamp types with safety, costs or public reaction. Names and phone numbers of persons to contact for further information were requested. No instance of confusion in answering the questionnaire was reported.

B4.1 Questionnaire

Of the 69 public agency contacts, 63 responses (91%) have been received, as shown in Table B13. Letters sent to the AASHTO, IES, ITE, and FHWA have received no response. Follow up calls found that ITE, IES, AASHTO and FHWA had no reports and knew of none pertaining to the subject issue. However, the EPRI contact identified one paper of significance and the LRC identified nine others. These are listed in the bibliography. E-mails sent by consultant Richard Stark to foreign contacts resulted in only three responses.

TABLE B13. CONTACTS

Agency	Questionnaires sent	Follow ups	Answers
States	49	19	46
Canadian Provinces	3	1	3
U.S. & Canadian Cities	17	3	14
TOTALS	69	23	63

TABLE B14. QUESTIONNAIRE FINDING RE LAMP TYPES AND ROUTES

Agency	Lamp Types	Routes Where Lamps Used[a]			Reports
		Freeways	Rural	Urban	
States	LPS	2		1	
	HPS	43	2	1	
	MH[b]	6	1	1	
Provinces	LPS		1[c]		
	HPS	1	1		
	MH				
Cities	LPS			4	
	HPS	2	1	13	
	MH	1		3	
Foreign	LPS	1			
	HPS	2	1	1	
	MH				
TOTALS	LPS	3	-	5	
	HPS	47	5	15	
	MH	7	1	4	
ALL		57	6	24	0

[a] If any significant LPS or MH lamp use.

[b] Also used on high mast interchange installations by three states.

[c] Intersections only.

Table B14 summarizes questionnaire findings received to date. Relative to use of LPS, there were five freeway and three urban street locations (cities or states) identified. HPS was the predominant type of lamp used by both cities and states, with 67 locations found.

There were 12 locations using MH lamps, plus three more (states) with interchange high mast MH.

Only one agency identified a report relative to lamp type --an old one comparing HPS with mercury. No public agency reported any studies that correlated accident numbers or types with LPS, HPS and/or MH roadway lighting.

B4.1.1 Low Pressure Sodium

The most significant locations found using LPS lamps were the cities of San Jose, California and Glendale, Arizona. They also are used in Flagstaff, Arizona, two miles in Los Angeles, four miles in Toronto, and four miles in Texas. These involve urban major streets. Tucson uses LPS on local subdivision streets, however this is not applicable in the subject project. San Jose reported 2,200 miles of LPS, with HPS only in the Central Business District (CBD). Only two freeways were found with LPS in the U.S., Iowa and California, and these were reported as having few such lamps. Toronto reported three miles of elevated freeway with LPS. Alberta reported approximately 100 rural intersections with LPS.

B4.1.2 High Pressure Sodium

For freeway and rural highway, HPS was the lamp of choice found in over 80 percent of the cases. In urban applications, 63 percent used HPS.

B4.1.3 Metal Halide

MH use was reported on freeways in Maine and Tennessee. Maine has an estimated three miles of MH and 10 miles of HPS freeway lighting. Delaware listed MH use by one contact, but this was questioned by another. The major source of urban street MH use found is Toronto, reporting 38,000 MH fixtures and 130,000 HPS. Toronto is the location found to date with the largest numbers of MH lamps and presumably widely varying illumination levels to compare with HPS. Los Angeles reported 39 miles of MH use on urban streets and over 4,400 miles of HPS use. Contacts also were made relative to type of MH lamp used (probe, pulse or ceramic). Three agencies reported using pulse and three using ceramic.

The only policy found was in the City of Milwaukee, to replace all existing MH with HPS upon burnout.

B4.1.4 Summary

The relative effect of lamp type on performance, maintenance, life-cycle cost or safety apparently has not been researched by public agencies. The survey has, however, secured valuable data on locations for possible field study in a future project, including contact personnel and general limitations on probable cooperation.

B4.2 Accident Findings From Literature Search

While the literature search was aimed toward location of any safety studies relating safety to lamp type, available data on accidents for several road types, plus the effects of lighting reductions, have been obtained and are summarized. Also included are data from numerous studies of night traffic percent, variable in-service lamp depreciation, benefit-cost analysis of lighting and of group-replacement policies.

An extensive search was made by Paul Box in the late 1980s on behalf of the IESNA Roadway Lighting Committee and reported in *The Value of Roadway Lighting*.[1] A draft copy of the proposed update of this publication has been reviewed also, but no significant added studies were found to be included.[1] No studies of comparative lighting effects on accidents as related to lamp type have been identified.

B4.2.1 Freeways

B4.2.1.1 The most significant study of freeway accidents by the U.S. related to lighting was jointly sponsored by the IES and the (then) Automotive Safety Foundation, and reported as *Relationship Between Illumination and Freeway Accidents*[2] The project gathered data on over 21,000 accidents along 195 miles of freeways in six U.S. cities and in Toronto, Canada. Of the 35 urban or suburban sections, 28 were lighted and seven were unlighted. The routes ranged from 4-lane to 10-lane widths. All lighting used mercury lamps, of 400-watt size, except one freeway in Texas with 700-watt lamps. Data on other lighting elements were gathered. The principal project findings, expanded to add tables, figures and later references, are given below:

B4.2.1.2 Lighted urban freeways have a significantly lower night accident potential than unlighted ones. An average reduction of 40 percent in night accidents can be predicted as a result of lighting, or an 18 percent reduction of total, day plus night, accidents.

B4.2.1.3 The calculated Benefit-Cost Ratio, using a 20-year lighting amortization, was found to be 2.3 for freeways with four lanes, 1.4 for six lanes, and 1.7 for eight or ten lanes.

B4.2.1.4 The comparison of lighted with unlighted routes was made by three different methods; all lighted versus all unlighted sections; lighted versus unlighted sections of the same route; and on sections having before-and-after accident data. In each case, the lighted freeway sections had lower (better) average ratios of night/day accident rates.

B4.2.1.5 Field measurements were made of existing freeway lighting at 14 locations, and did not confirm calculated in-service values. Therefore, data previously gathered on 18,000 accidents for the Public Lighting Needs study done for the U.S. Congress could not be used, since measurements were not available for these routes.

B4.2.1.6 Freeways, with measured “typical” in-service illumination levels between 0.3 and 0.6 HFC (horizontal footcandles) had the best accident rate ratios; however maintained illumination found in the lighting systems ranged from 28 percent to 82 percent of initial values, with an average of 50 percent. Typically, an initial design value of 1.0 HFC was required to produce the in-service illumination on the group of freeways having the best accident rate ratio.

B4.2.1.7 A great variation was found in luminaire output in the field. In eight different freeway sections, readings were taken below several adjacent luminaires, and approximate illumination values were calculated between more than 60 pairs of adjacent units. When compared with the “average” from the point-by-point area measurements within each test location, HFC variations were found as low as 67 percent below the average to as high as 60 percent above it.

B4.2.1.8 HFC variations within sections of routes where maintenance was by replacement of lamps only after burnout were checked against the variations of sections having group-replacement maintenance. No significant difference was found in the extreme range average under either type of maintenance. A separate check of systems having different types of maintenance found an average depreciation of 54 percent for burnout (spot) replacement versus only 36 percent for group replacement methods. This suggests that the variation problem may be due to inconsistent lamp output more than the maintenance procedure.

B4.2.1.9 Data were analyzed from over 800 mercury lamps taken from the field after lengths of service ranging between a few months and 10 years. The illumination output was checked as a percent of control lamps (used to simulate “initial” lamp performance). Wide variation was found, with lamps less than two years old producing 54 percent to 98 percent of nominal output, those between two and three years old producing 46 percent to 94 percent, and those three to four years old producing 40 percent to 94 percent. The average output was 67 percent of nominal.

B4.2.1.10 The uniformity ratios for HFC and VFC (vertical footcandles) were checked on both an average-to-minimum and on a maximum-to-minimum basis at several locations. No meaningful relationships were found with accident rate ratios. The wide fluctuations found in luminaire and/or lamp output also resulted in extreme spreads of actual uniformities between different units along each route. On one freeway, the “typical” uniformity was 15 to 1, but a nearby uniformity was 6.6 to 1, and another was 22 to 1.

B4.2.1.11 Due to the inconsistent depreciation rates of 400-watt mercury lamps as found under actual field conditions, the commonly accepted roadway lighting system design elements of “average HFC” and “uniformity” appear to be nearly meaningless. The driver is typically exposed to wide ranges in both of these values. These variations are in addition to the undulating illumination and glare that is visually experienced in driving between one luminaire and the next.

B4.2.1.12 During the initial stages of the research, a method was developed to specify that level of ambient (natural daylight) illumination when typical roadway lighting can become effective. This moment of “darkness” occurs at the point one-sixth of the way between local Astronomic Twilight and the sunrise or sunset. It is approximately 15 minutes before sunrise and 15 minutes after sunset (see Figure B3).

B4.2.1.13 Using the above method of specifying the darkness point, the actual vehicle-miles of night and day traffic were checked for freeways in widely separated areas. In all cases, the annual average night travel was found to be 25 percent of the total, irrespective of latitude or Daylight Saving Time practices. This is a particularly important finding from the research standpoint, since it allows calculation of the night/day accident rate ratio even in the absence of detailed travel mileage (see Table B9 and Figure B4). Other studies have found a similar value; Paul Box in Kansas City, Missouri,[3] Billion and Parson on Long Island, New York,[4] McCoy et al in Nebraska.[5] Table B16 shows further findings by Box in Maryland, Maine, and Dallas, Texas.[6] However, Bruneau et al, found only 21 percent in Quebec.[7]

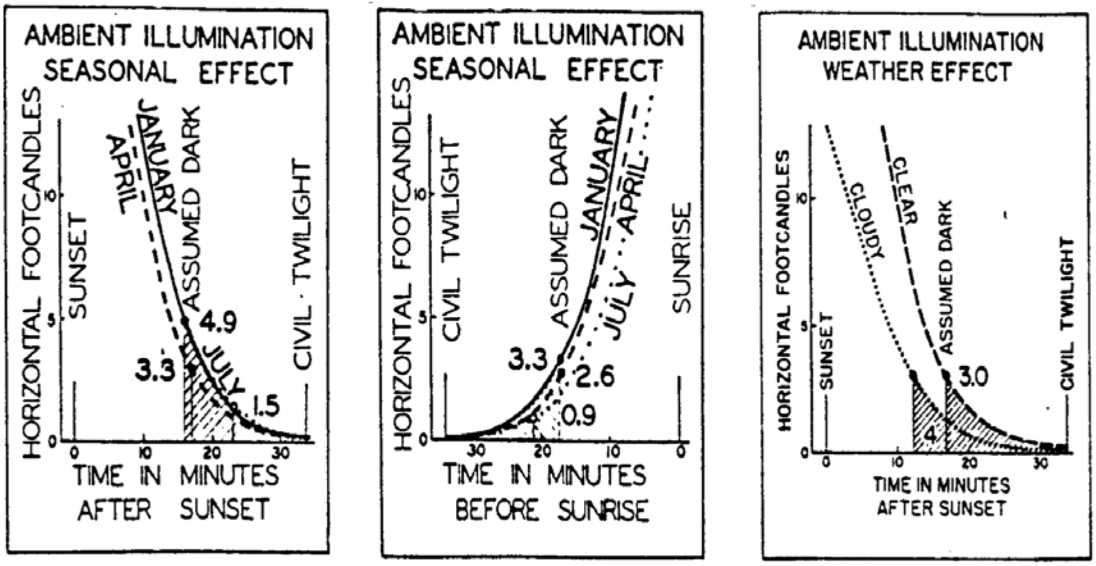

Figure B3. Ambient Illumination Changes

Source: Figures 2, 3 and 4 from Ref. 2.

TABLE B15. NIGHT TRAFFIC PROPORTIONS

	Average from Mid-Month Week Sample (84 Days)	True Annual Average (365 Days)
TORONTO		
RT.400 - Suburban	27.7 %	25.8 %
RT. 401 - Urban	26.0 %	--
RT. 401 - Rural	25.6 %	–
QEW - Urban	26.4 %	–
Area Average	26.4 %	--
CHICAGO		
I-294 - Suburban	–	25.8 %
DALLAS		
I-20 - Urban	–	26.1 %
I-35 - Urban	–	23.8 %
US 75 - Urban	–	23.9 %
Area Average	–	24.6 %
ATLANTA (No Daylight Saving Time)		
I-75 - Suburban	25.6 %	–
I-85 - Suburban	25.6 %	–
DENVER		
I-25 - Urban	22.8 %	–
PHOENIX		
I-10 - Urban	24.2 %	–
AVERAGE ALL	25.5 %	25.1 %

Source: Ref. 2.

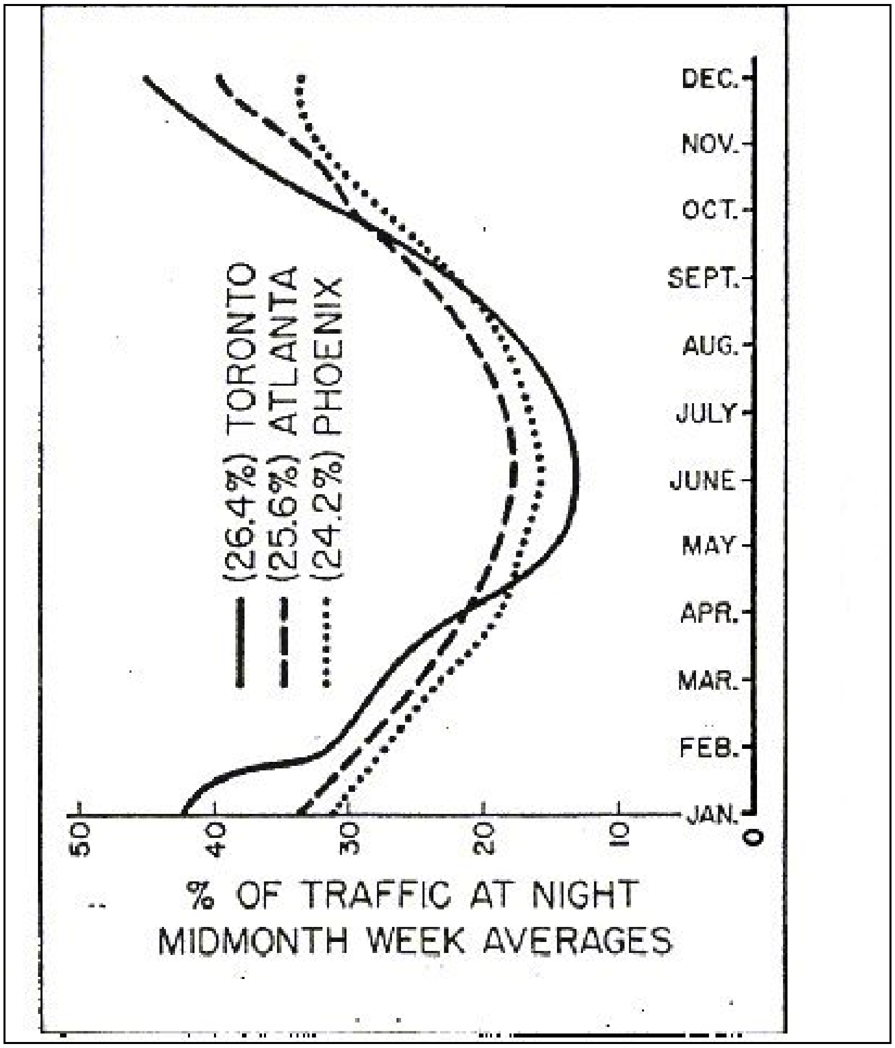

Figure B4. Night Traffic Monthly Variation

Source: Figure 5 of Ref. 2

TABLE B16. PERCENT OF NIGHT TRAFFIC

Year	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept	Oct.	Nov.	Dec.	Annual Average
MARYLAND I-70, WEST OF FREDERICK (RURAL)													
1972	41.6	36.3	30.6	25.8	19.7	17.4	17.9	20.4	26.4	31.8	41.0	47.5	28.1
1976	40.5	36.5	28.8	24.4	20.3	17.7	17.9	20.8	25.9	30.8	39.8	44.4	27.7
MARYLAND I-95, BETWEEN BALTIMORE AND WASHINGTON (URBAN)													
1972	36.6	27.6	25.2	21.2	16.6	15.6	16.5	18.4	22.7	25.8	37.0	39.0	24.3
1976	34.9	31.9	26.6	22.7	18.4	16.0	16.5	18.6	25.1	29.9	36.9	41.2	26.1
MAINE I-95, BETWEEN AUGUSTA AND HOULTON (RURAL)													
1972	38.7	35.3	32.4	24.7	18.1	13.8	12.7	14.0	19.6	27.8	41.2	44.7	24.6
1976	40.7	33.4	27.6	23.5	15.3	12.9	12.5	14.0	18.3	24.9	40.2	42.4	23.7
MINNESOTA, I-35N, NORTH OF ST. PAUL (RURAL)													
1972	44.7	35.3	26.7	19.8	14.4	11.8	12.3	15.6	22.9	30.7	43.7	46.4	24.6
1974	42.4	33.1	26.2	13.4	14.6	11.6	12.9	14.9	22.8	27.5	45.0	46.1	23.9
1975	43.5	35.2	26.1	17.7	13.8	11.4	12.0	16.1	22.7	29.9	42.8	45.7	24.0
MINNESOTA, I-494S, EAST OF CEDAR STREET (URBAN)													
1972	43.4	31.4	25.1	20.1	14.2	12.7	13.2	17.5	21.2	27.5	38.6	44.6	25.4
1974	41.3	35.0	25.1	17.5	13.8	12.6	13.3	15.6	20.6	27.7	37.2	44.1	24.8
1975	40.6	32.3	24.2	17.4	14.7	12.6	13.1	16.1	19.0	26.0	37.0	46.3	24.2
DALLAS, I-635, WEST OF U.S. 75 (URBAN)													
1974	31.5	27.1	21.4	16.5	13.5	12.2	12.7	15.7	18.3	23.1	29.1	31.8	21.0
1975	30.3	29.7	21.9	16.8	13.8	12.7	13.4	15.9	18.8	24.2	30.5	33.4	21.7
1976	30.7	24.9	21.7	19.1	14.5	12.9	13.1	16.5	19.2	23.8	28.6	32.8	21.4
DALLAS, U.S. 75, NORTH OF CBD (URBAN)													
1974	34.1	29.6	23.7	18.4	15.4	14.3	14.4	17.3	20.2	26.5	30.2	32.6	22.9
1975	31.3	27.6	24.4	19.1	16.1	14.7	15.1	17.7	20.6	27.5	30.6	32.6	23.1
1976	31.7	27.2	23.4	20.4	16.9	15.0	16.0	17.9	21.4	25.8	29.6	34.7	23.2

Source: Ref. 6 Note that data is approximately 25 years old and its present day applicability is uncertain.

B4.2.1.14 In a sample of five freeway sections, an average of 50 percent of the accidents was found to occur between the interchanges. Furthermore, the areas between interchanges typically had a higher percent of accidents at night than within the interchanges. This tends to indicate that if any lighting is provided it should be on a continuous basis.

B4.2.1.15 Drivers of age 40 and over had more than one-fourth of the total day and night accidents on each of the lighted and unlighted sections of one route. However, of these accidents involving the older group, only 18 percent occurred at night in the lighted section versus 29 percent at night in the unlighted section.

B4.2.1.16 The Bruneau study[7] also represents a major study of motorway (freeway) accidents related to lighting. A database of 22,740 accidents on 480 miles of Quebec routes was used. The analysis was based on a night/day accident rate ratio method to compare the safety benefits of two alternatives to dark motorways: continuous lighting and interchange lighting alone. Various sources of data were used to calculate night/day accident rate ratios, such as traffic volume records, accident databases, and field surveys. Three categories of accidents were used: fatal and injury accidents, property damage only, and all accidents. Continuous lighting was found to reduce the overall accident rate by 33 percent ($p = .001$) in comparison with interchange lighting alone and by 49 percent ($p = .05$) compared with dark motorways. Furthermore, a breakdown by categories of average daily traffic for these comparisons revealed that accident reductions were valid regardless of traffic flow. Table B17 summarizes data.

B4.2.1.17 Frankfurt --Suburban Freeway. In Germany, the Frankfurt study[8] analyzed about 1,900 accidents reported from 1972 through 1981 on 4.7 miles of a 4-lane freeway. The route was divided into three sections. Two were lighted, while the third section was used as a control. The study involved before-and-after lighting data, plus a lighting reduction condition. One section showed no improvement in the night/day ratio of accident rates as a result of lighting, while the second section showed a rate reduction of 17 percent. However, the rate in the unlighted control section increased 38 percent. If a similar relationship were to be assumed for the two lighted sections, then an accident reduction related to lighting effect would be found on both of these sections.

B4.2.1.18 Netherlands --Rural Freeways. The CIE report[9] includes a study of 82 miles of lighted and 469 miles of unlighted rural freeways in the Netherlands. The accident sample was over 6,300 and the ratio of night/day accidents for the unlighted routes was found to be 28 percent greater than for the lighted routes.

B4.2.1.19 Paris --Al Motorway. The 1992 CIE report study #46 found night accidents to be reduced 43 percent after lightig a trial section versus an increase of 30 percent in a control section.[9] The accident sample was only 59 accidents, however the author reported statistical significance at the 5 percent level.

TABLE B17. QUEBEC FREEWAY NIGHT/DAY ACCIDENT RATE RATIOS

	Continuous Lighting	Interchange Lighting			Unlighted
		Partial	Complete	TOTAL	
ADT: <20,000					
Fatal-Injury	1.67	1.80	1.79	1.78	1.99
PDO	0.86	2.09	2.00	2.01	2.45
Total	0.98	2.03	1.98	1.97	2.00
ADT: 20,000-40,000					
Fatal-Injury	1.09	1.81	1.80	1.80	1.74
PDO	1.06	2.23	1.78	1.89	1.76
Total	1.07	2.14	1.78	1.87	1.76
ADT: >40,000					
Fatal-Injury	1.60	--	1.79	1.75	–
PDO	1.37	2.25	1.69	1.69	–
Total	1.41	1.80	1.70	1.70	--
TOTAL					
Fatal-injury	1.50	1.75	1.80	1.78	1.90
PDO	1.24	2.11	1.84	1.91	2.18
Total	1.28	2.04	1.84	1.89	1.91

Source: Ref. 7. ADT = Average Daily Traffic. PDO = Property Damage Only.

B4.2.1.20 Japan --Meishin Motorway. The 1992 CIE report study #48 involved 7.8 miles, with a before-and-after accident sample of 383.[9] For dry conditions, night accidents were 48 percent of the total before lighting versus 29 percent after. For wet pavement, night accidents were 44 percent before and 30 percent after. Overall, the day plus night accident rate/million miles was reduced of 20 percent. This closely approximates the U.S. finding of 18 percent overall.[2]

B4.2.1.21 Summary. The six cited studies drawn from over 52,000 accidents on nearly 780 miles of freeways strongly indicate a value in the illumination of freeways. Both U.S. and foreign studies have found statistically significant accident reductions by the lighting of freeways. Furthermore, continuous lighting have been found to be of benefit rather than at interchanges only.

The U.S. finding that 25 percent of freeway accidents occur at night greatly simplifies comparative analysis by eliminating any need for volume data. It allows direct use of the night percent of accidents, rather than requiring a night-to-day ratio of rates.

B4.2.2 Highways and Rural Locations[1]

B4.2.2.1 Nashville --Davidson County. This Tennessee Davidson County study[10] covered four suburban highways totaling 30 miles. The accident records for one year prior to lighting in 1965, and two years after, involved 2,528 collisions. The night accidents were reduced 22 percent and injuries by 39 percent during the after period; however, day accidents were also lower, and the night/day ratio of accident rates per million vehicle miles showed an overall benefit of a 15 percent reduction.

B4.2.2.2 Primary Road Rural Intersections. The Iowa 3-year before-and-after study[11] covered 47 locations and 568 accidents. Overall, the night accident rate of 1.89 per million entering vehicles (before) dropped to 0.91 after lights were installed; a reduction of 52 percent. The lighting was of greatest benefit at intersections having raised concrete channelization, with a route turn and having four legs. Also, intersections with the largest number of lights installed had the greatest accident reduction (see Table B18).

B4.2.2.3 Illinois --Rural Intersection Street Lighting. The Illinois study[12] used accident data from 182 unlighted intersections and 263 lighted intersections (one intersection for one year). The night/day ratio of accidents per million entering vehicles was reduced 25 percent. The night accident rate alone was reduced 45 percent. Furthermore, intersections with channelization, but no lighting, had higher ratios than those with both lighting and channelization.

TABLE B18. DATA FROM IOWA PRIMARY ROAD RURAL INTERSECTION STUDY

Intersection	Number in Test	Night/Day Ratios of Accident Rate		
		Before	After	Change (%)
Channelized	28	1.31	0.69	- 47
Non-channelized	19	1.05	0.63	- 40
With route turn	21	1.53	0.80	- 48
Without route turn	26	0.92	0.55	- 40
Three legs	15	1.14	1.01	- 11
Four legs	32	1.23	0.51	- 59
3 to 5 lights	19	0.94	0.84	- 11
6 to 9 lights	21	1.27	0.72	- 43
10 to 15 lights	7	1.61	0.32	- 80

Effect of channelization, route, turn, number of legs, and intersections by number of lights on accident rate per million entering vehicles.
Source: Ref. 12.

B4.2.2.4 Greece --National Highways. The 3-year study[13] in Greece of 11 miles of illuminated highways and 9 miles of unlighted highways involved 759 accidents. The lighted highways had only 27 percent of accidents occurring at night versus 37 percent for the unlighted ones.

B4.2.2.5 France --Rural Intersections. A French study[14] of 82 lighted and 85 unlighted rural intersections on the outskirts of Paris, Lyons and Marseille included 1,347 accidents over a 4-year period. With lighting, 31 percent of accidents occurred at night, while the locations without lighting had 43 percent of their accidents at night.

4.2.2.6 Summary. These studies involved over 5,200 accidents on 51 miles of roads and hundreds of isolated intersections. Value has been found in lighting –- especially at intersections with raised curb channelization. Increases in the amount of illumination (as reflected by increases in the number of lights) appear to produce greater reductions in accidents. While it is seldom possible to warrant continuous rural highway lighting on a benefit-cost basis, a moderate expenditure for intersection lighting may be warranted, based on these studies.

B4.2.3 Urban Major Streets[1]

Data are available from studies conducted approximately 50 years ago. Their applicability to present day roadways is uncertain.

B4.2.3.1 Chicago --Major Street Fatal Accident Comparison.[15] A Chicago study compared fatal accidents on 512 miles of streets lighted during 1952 to 1958. In 1952 there were 156 fatal night accidents on these routes versus 81 in 1956; a reduction of 48 percent.

B4.2.3.2 Kansas City --Pedestrian Fatalities.[3] In 1945, Kansas City, Missouri began a major relighting program. Table B19 shows that from 1945 through 1947, 94 pedestrians were killed (70 at night). An average of three percent of the streets had modernized lighting during this period. As the lighting program progressed, the number of pedestrians killed was steadily reduced. From 1954 through 1956, with an average of 90 percent of the streets relighted, only 44 pedestrians were killed (13 at night). This is a reduction in night pedestrian accidents of 81 percent.

TABLE B19. PEDESTRIAN FATAL ACCIDENTS IN KANSAS CITY STUDY

Number of Fatal Accidents				Percent at Night
Year	Day	Night	Total	
1945	6	23	29	79
1946	9	32	41	78
1947	9	15	24	62
1948	18	14	32	44
1949	6	10	16	63
1950	8	8	16	50
1951	13	6	19	32
1952	12	4	16	25
1953	15	9	24	37
1954	9	6	15	40
1955	9	4	13	31
1956	13	3	16	19

Source: Ref. 3. Expanded to include 1955 and 1956 data.

Furthermore, traffic volume studies found 25 percent of travel at night for Kansas City as a whole. At the beginning of the lighting program, nearly 80 percent of the pedestrian deaths were at night versus less than 30 percent in the after-period. By 1956, the figure dropped to only 19 percent at night. During the entire 12-year period, an estimated 140 pedestrian lives were saved by the new lighting.

B4.2.3.3 Long Island --Major Routes with Mountable Median. As part of a widespread study[4] comparison was made of accidents on three unlighted sections totaling 6 miles and on three lighted sections totaling six miles. A total of 539 accidents were tabulated during approximately four years. From the data, it has been calculated that the night/day rate per million miles of the unlighted sections was 1.5 times that of the lighted sections.

B4.2.3.4 New South Wales --Street Lighting Improvements. From 1966 through 1969, New South Wales, Australia conducted a study for various sections of roadways, each about one mile in length, for which lighting was upgraded to give approximately 15 times the quantity of light, to control glare and to conform to the *Standards Association of Australia Street Lighting Code*.(16) The study covered about 60 miles of road sections on which accident statistics were recorded for two years before and two years after modernization of the lighting. The decrease in the relative nighttime accident rate was some 21 percent, with decreases in fatality rates of about 29 percent including a decrease in the pedestrian fatality rate of 57 percent.

B4.2.3.5 Syracuse --Accidents Related to Illumination. In 1967, a Syracuse, New York study used data on approximately 7,500 accidents on nearly 100 miles of major and collector streets.[17] Those streets with little or no illumination were found to have substantially higher (poorer) night-day accident ratios and accident cost ratios than the average for all streets in the same roadway functional classification and type of abutting land use. Also, the type of street appeared to be more of a factor in accident-illumination relation than the type of abutting land use.

B4.2.3.6 Naperville --Ogden Avenue. A 1988 study in Naperville, Illinois, used two years of before-data and two years after-data on the effects of lighting a 1.7 mile length of a five-lane major traffic route.[18] The accident sample exceeded 800. Table B20 indicates the changes in the accident proportions at night. The reduction in night accidents per million vehicle miles was 36 percent, corresponding to a reduction in total, day plus night accidents, of 14 percent. This study also involved field measurement of the installed system at the six-month point. The measured average illumination was five percent greater than calculated after allowing for the HPS lamp life depreciation. The average-to-minimum uniformity ratio was within 10 percent of calculated. Luminance, illuminance and Small Target Visibility calculations showed the design to fully comply with IES RP-8 recommendations.

TABLE B20. DATA FROM OGDEN AVENUE STUDY

	Night Percent Before	Night Percent After
Pedestrian and bicycle type	60	29
Fixed object type	64	25
All midblock	35	21
Overall accidents	31	23

Source: Ref. 19

B4.2.3.7 Worldwide Studies. The International Commission on Illumination (CIE) reviewed over 60 studies. They identified 40 which they calculated to have statistically significant results.[9] Reductions in nighttime accidents, following installation of good or improved roadway lighting, ranged from nine to 75 percent. Their findings also mirror the Kansas City, Missouri, experience, that urban street lighting most benefits the pedestrian. This kind of accident was reduced by 45 to 57 percent by lighting versus 21 to 23 percent reductions for other types of accidents.

B4.2.3.8 Summary. More than 9,300 accidents were identified on over 660 miles of streets in these studies. It is clear that the major beneficiary of urban major street lighting is the pedestrian/bicyclist, with fixed object type accidents also reduced. It also is well established that lighting of major, as well as other urban streets, adds benefits in perceived personal security of road users. Furthermore, the findings of three studies[3, 4, 5] that 25 percent of urban street traffic moves at night, also simplifies analysis of urban accidents.

B4.2.4 Lighting Reduction[1]

Most available data are old. Their applicability to present day conditions is uncertain.

B4.2.4.1 General. The oil embargo of 1973-74 resulted in worldwide cutbacks of illumination as an energy conservation measure. Several detailed studies have been made of lighting reductions or turnoffs since that time, and the following studies illustrate how reduction of continuous or full interchange lighting resulted in accident increases.

B4.2.4.2 Austin, Texas --I-35. Lighting was turned off on the southbound lanes of I-35 for a length of 6.8 miles, while no change was made in the northbound lane lighting or the ramps.[19] Two years of before-data and two years of after-data involved 550 total accidents on the mainlines. Before the change, 23 percent of the accidents occurred at night. After the change, both day and night accidents were reduced by 25 percent (likely due to less driving and possibly the 55 mph speed limit); however, on freeway mainlines where the lights were turned out, day accidents went down 17 percent while night accidents increased 47 percent.

B4.2.4.3 Freeway Interchanges. Two fully lighted urban interchanges in Utah were studied in 1972/1973 and in 1976 with about 75 percent of the lights operating.[6] The night/day ratio of accident rates (based on travel exposure) increased from 1.2 to 1.8 (50 percent). Two urban interchanges in Minnesota also were studied for two years after lighting was reduced to about 55 percent. With the reduction, the night/day ratio of accident rates increased from 2.2 to 2.8 (27 percent). These four locations had a total of 286 accidents across the total study period. Studies also were made of partially lighted interchanges at 41 rural and 22 urban locations. These typically had three to five lights, only at the ramp connections with the mainline. Based on a total before-and-after accident sample of 947, no significant effect was found when about 50 percent of these lights were turned off.

B4.2.4.4 Dallas --Continuously Lighted Freeways. A study was made using two years of full lighting (1974 and 1975) with one year (1976) of reduced lighting.[6] On I-635, a fully lighted route with about 1,400 total accidents sampled in a 11.8 mile section, the night/day ratio of accident rates increased from 1.0 to 1.2 (20 percent), when lighting was reduced to about 38 percent of original. Another freeway, U.S. 75, with over 4,900 accidents tabulated in 6.9 miles had lighting reduced to 62 percent of original. It had no change in the night/day ratio of accident rates; however, it was not lighted to appropriate levels before the change.

B.2.4.5 Frankfurt Study. Lighting of one of the three sections of roadway was turned off between 22:00 and 05:30 hours.[8] The night/day ratio of accident rates (per million vehicle miles of travel) increased 60 percent.

B4.2.4.6 Belgium Motorways. Lighting was switched off between 03:00 and 05:30 hours on 360 miles of motorways.[20] No change was made on 93 miles which acted as a control. Based upon a sample of nearly 300 accidents that occurred during this time period, in a one year before and one year after study, an increase of six percent was found in accidents. More importantly, deaths increased 38 percent and serious injuries increased 108 percent.

On another 573 miles of motorways, the lighting was reduced to 50 percent. From a before-and-after accident sample of about 750, it was concluded that all accidents increased 25 percent, deaths 10 percent, and serious injuries 99 percent.

B4.2.4.7 Summary. Studies of reduced illumination show that some effects may occur, and are indeed likely, if the route was well lighted before the change. Conversely, partially or poorly lighted routes show little or no effect.

B4.3 General Summary of Accident Studies

This review has covered lighting benefits on freeways, rural roads, intersections, and urban major streets, plus hundreds of intersections or interchanges. Findings of particular significance are:

- Freeway lighting can result in overall accident reductions of 18 to 20 percent.
- Continuous freeway lighting is substantially better than interchange-only lighting.
- Rural intersection lighting can reduce overall accidents by about 25 percent.
- Urban major street lighting can reduce overall accidents by 14 percent or more, with much greater reductions in pedestrian or bicycle night accidents.
- Reducing illumination levels of a well-lighted freeway, as an economy effort, can result in greater numbers of accidents at night.
- About 25 percent of freeway and urban major street travel occurs at night.

While it is recognized that the main focus of this research program was to determine the relationship between safety and lamp type, unfortunately no data have been found on safety effects as applied to different lamp types.

ADDENDUM

PAUL C. BOX and ASSOCIATES, INC.
TRAFFIC ENGINEERING CONSULTANTS
Founded 1966
PAUL C. BOX, PRESIDENT
8366 Via de Viva, Scottsdale, AZ 85258
(480) 998-2567 FAX (480) 998-2568

TO: ___________________________

FROM: Paul C. Box, Research Consultant to Lighting
Sciences of Scottsdale, AZ; Ian Lewin, Principal

DATE: ________________

Lighting Sciences has entered into a contract with the AZ DOT to investigate and evaluate any differences in safety and economy of installation/maintenance of highway lighting, relative to type of lamps used. If such information might better be supplied by someone other than yourself, it would be appreciated if you would forward this questionnaire to them.

1. Do you have freeways or major streets using luminaires with:

	Yes	No
1. LPS (low pressure sodium lamps)	___	___
2. HPS (high pressure sodium lamps)	___	___
3. MH (metal halide lamps)	___	___

2. If you have no significant LPS or MH lamp usage, please disregard the balance of these questions, and enter the information in #8 and mail or FAX to the above address.

   If you have freeways, rural highways or urban streets using lighting with significant numbers of LPS or MH lamps, please answer the following questions.

3. Approximate mileage of several routes, having:

   1. LPS; freeways ______; rural hwys ______; urban sts ______
   2. HPS; freeways ______; rural hwys ______; urban sts ______
   3. MH; freeways ______; rural hwys ______; urban sts ______

4. Identification of person we can contact relative to:

   1. Lighting design;
      name______________________________ Phone # ______________

   2. Lighting maintenance;
      name ______________________________ Phone # ______________

   3. Accident data;
      name ______________________________ Phone # ______________.

5. Has your agency, or any other agency you can identify, ever conducted a study of comparative safety, costs, or public reaction as a function of <u>lamp type</u>:

		Yes	No
1.	LPS	___	___
2.	HPS	___	___
3.	MH	___	___

   4. Copy available ___ ___

   5. Name and date of report __________________________________

   ____

6. If the answer to any part of #5 is ‘yes’, who can we contact relative to:

1. Obtaining a copy of the study:
   name ______________________________ Phone #______________

2. Further information on lighting design:
   name ______________________________ Phone #______________

3. Further information on accident data:
   name ______________________________ Phone #______________

4. Further information on installation costs:
   name ______________________________ Phone #______________

5. Further information on maintenance costs:
   name ______________________________ Phone #______________

7. In the event we, or other researchers, were authorized as part of a future field data collection effort to secure accident data, would your office cooperate by making access available to your files? Yes ___ No___

8. These questionnaire answers prepared by:

   Name ____

   Title ____

   Address____

   ____

   ____

   Phone #_____________________ FAX # _______________________

Thank you for your cooperation.

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APPENDIX C

RESEARCH PLAN FOR THE INVESTIGATION OF THE IMPACT OF LIGHT SOURCE SPECTRAL DISTRIBUTION AND LIGHTING LEVEL ON VISIBILITY AND SAFETY

Reference: Research Topic SPR 522-1

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April 2003

APPENDIX C

RESEARCH PLAN FOR THE INVESTIGATION OF THE IMPACT OF LIGHT SOURCE SPECTRAL DISTRIBUTION AND LIGHTING LEVEL ON VISIBILITY AND SAFETY

C1. PROBLEM STATEMENT

C1.1 Numerous factors associated with roadway lighting influence the level of visibility that may be created. Such visibility, in turn, is likely to affect the level of safety. These factors include light level, glare, lighting uniformity, and light source spectral distribution.

C1.2 For a given set of lighting conditions, the nature of the visual task is likely to have strong influence. Under typical nighttime driving conditions, such visual tasks are highly variable.

C1.3 The Illuminating Engineering Society of North America publication ANSI/IESNA RP-8-00, "Recommended Practice for Roadway Lighting," categorizes 14 different roadway types and conditions. For each, a different set of recommended lighting levels, uniformities and glare limits are provided.

C1.4 The IESNA recommendations are based on the consensus of persons knowledgeable in the field. While laboratory and field research has contributed to the knowledge base in this subject, no overall field research program to study lighting levels and their relationship to safety for varying highway and visual task conditions has been conducted. Therefore, IESNA recommendations and other recommendations based on IESNA values are questionable.

C1.5 Several factors have a strong influence on visibility and therefore presumably safety, including lighting level and its uniformity. Light source type, particularly with regard to spectral distribution, evolved as a topic of considerable interest in recent years. Laboratory studies have indicated that different spectral distributions, or light source colors, can strongly influence visibility under some circumstances. It may be expected that this, in turn, will influence safety.

C1.6 The degree to which spectral distribution can influence visibility is dependent upon several factors, one such factor being light level. It is likely, therefore, that for roadways lighted to different levels, the influence of spectral distribution on visibility and safety will also differ. There are probably a complex inter-relationships between light levels, lamp type, visibility and safety. The nature of these relationship is not well understood.

C1.7 An additional factor that is believed to influence visibility and safety as related to spectral distribution is the nature of the roadway visual task. Certain tasks may be strongly influenced, while others may indicate little or no change in visibility under different lamp spectra. The interrelationship between task type, spectral distribution and visibility is not well understood.

C1.8 A fully coordinated study is needed to relate nighttime safety to lighting level, visual task type and lamp spectral distribution. The study results might form the basis of future roadway lighting recommendations. This may lead to improved safety and/or lower life cycle costs for lighting systems.

C2. RESEARCH OBJECTIVES

C2.1 Identify significant safety-related visual tasks that may be influenced by the lighting system.

C2.2 Investigate under controlled conditions and differing light levels the capability of drivers to conduct such visual tasks and react accordingly.

C2.3 Investigate under controlled conditions and different lamp spectral distributions the capability of drivers to conduct such visual tasks and respond accordingly.

C2.4 Develop a matrix of test results for various visual tasks, lighting levels and lamp spectral distributions, as they relate to safety.

C2.5 Include the effect of variable weather conditions to whatever extent is possible.

C2.6 Identify lighting system costs and other non-safety factors such as unit power density, light pollution and HAZMAT issues for the various test systems.

C2.7 Develop a set of recommendations relating driving and roadway conditions, lighting levels and lamp spectral distribution to safety, for possible inclusion into future ADOT lighting practice. This must include younger and older drivers. The information may be useful to ADOT and may have national and international significance.

C2.8 The reflected light from the pavement and other surfaces is to be considered for each set of test conditions, as this will affect light pollution.

C3. RESEARCH TASKS

C3.1 Driver Visual Tasks

C3.1.1a. Conduct a literature search to identify driver nighttime visual tasks. Give particular attention to task location with respect to driver sight lines. Emphasize realistic tasks and situations. Further identify kinds of visual task failures that lead to accidents, and the relative importance of the identified failures as measured by the total number of accidents caused. Examples might include the failure to detect in time for avoidance an off-roadway animal headed on a collision course, or failure to detect in time for avoidance a hazard in the roadway in poor weather.

C3.1.1.b. Consider what has been done in past research and the problems encountered. Devise a research plan to avoid these pitfalls. Do not repeat previous uncontested research (example: eye scans indicating where motorists look while driving). This information (Rockwell, et al) was done under actual driving conditions. Motorist's driving psychology must be considered as forming the basis for driver's reaction to the scene (Lunenfeld and King). When does the motorist look off axis? Is the motorist paying attention to the periphery when under stressful driving conditions?

Color of the visual task may be an important variable, and this factor should be addressed during task selection.

C3.1.2 Make site visits to other lighting research facilities. This should include the Philips lab in France, Thorne lab in France, the Smart Road in Virginia, and GE and other manufacturers' outdoor lighting labs.

C3.1.3 Select visual tasks considered significant regarding safety.

C3.1.4 Develop a research plan to field test these visual tasks in a controlled environment. Consider, for example, imitation deer and human dummies at roadside.

C3.1.5 Identify the roadway elements and geometric features needed for field tests involving the selected visual tasks. Give attention to both straight-ahead tasks and peripheral tasks. This will include identifying the roadway width, length and nature of the peripheral areas. This should include the ability to simulate visual conditions at intersections.

C3.2 Lighting System Specifications

C3.2.1 Identify lighting system variables for the test roadway. Variables may include, but are not limited to: Lamp type, lighting level, uniformity, glare (from overhead luminaires, oncoming traffic and off-roadway), and how the lighting level should be quantified (illuminance, luminance, Small Target Visibility or other methods).

C3.2.2 Develop specifications for the lighting system configuration. The specifications shall include the following parameters at a minimum: pole layouts, luminaire mounting height and overhang, single versus multiple luminaires on a pole, fixed versus variable geometry, and dimming. Detail how changing the variables will be achieved: moveable poles, changeable mounting heights, dimming.

C3.2.3 Select three types of luminaires for the lighting systems, one each HPS, LPS and MH. Identify desired luminaire characteristics. Select luminaires with particular attention to providing equivalent photometric distributions for the three different lamp types, as far as is practical.

C3.2.4 Develop preliminary report of findings and produce outline of plans. Obtain review by outside specialists in vision research and roadway lighting. Modify per comments and suggestions received.

C3.3 Acquisition of Test Facility and Luminaires.

C3.3.1 Identify and detail methods of developing a test roadway. Consideration should be given to the following methods at a minimum: build a new facility dedicated to research, training, and testing; utilize an unopened section of highway for testing purposes and open the road to the public once the testing is completed; and use an abandoned site (airport or other paved facility) to simulate a roadway for testing purposes.

C3.3.2 Determine the necessary roadway geometrics of the test facility, i.e., minimum length and width, to simulate the various roadway classifications.

C3.3.3 Assist ADOT, or other authority, in a review of candidate test facilities.

C3.3.4 Develop complete set of contract documents, signed and sealed, for the installation of the roadway lighting test section.

C3.4 Luminaire Evaluations

C3.4.1 Test every acquired luminaire for photometric characteristics; create data base linking luminaire and its characteristics; and identify each luminaires placement in the lighting test section.

C3.4.2 Label each luminaire and verify its future location in the lighting system.

C3.4.3 Perform computer simulation of lighting test sections using the actual photometric data gathered in Section C3.4.1.

C3.4.4 Perform field lighting survey on newly-constructed lighting system. Identify discrepancies between predictive model and actual performance, and identify causal factors. Identify remedial action plan and calibrate lighting system model to factor in actual test results. Document all steps taken to calibrate model.

C3.4.5 Obtain reflectance measurements from pavement samples in accordance with ANSI/IES RP8-00. Perform computer modeling of pavement luminance characteristics.

C3.4.6 Determine required degree of similarity in lighting system measure identified in C3.2.1.

C3.5 Driver Response

C3.5.1 Define research measurement parameters based on literature search of driver response indicators. Possible measurements may include the following: driver discomfort; obstacle avoidance; and reaction time and braking.

C3.5.2 Write performance-based product specifications for the purchase of test equipment to measure the driver response indicators defined in Section C3.5.1. List examples, by make and model, of products which satisfy the specifications for each type of test apparatus.

C3.6 Experimental Design

C3.6.1 Develop a detailed test plan to investigate the possible effects of light levels and light source spectral distributions in relation to drivers' response in unexpected situations. The plan shall include, at a minimum, the following variables: a) lighting levels of zero; and below, at and above the current ADOT/IESNA/AASHTO levels; b) conditions with and without on-coming headlight glare; c) low-and high pressure sodium, and metal halide light sources; d) differing roadway geometry; e) differing travel speed; f) task randomness; and g) task color differentiation. The test plan shall consist of sufficient samples to produce results which are significant at a 95% confidence level.

C3.6.2 Specify conditions of the driver's headlamps, low or high beam. Specify the conditions of opposing headlamp glare to be used, assuming experiments will be conducted with and without opposing glare. Consider typical headlamp characteristics, which may not be the same as for new and clean headlamps. Consider also variable median widths to evaluate the mitigation of headlamp glare with varying light levels.

C3.6.4 Develop order of experiments, addressing randomness of presentation of differing conditions to the driver.

C3.6.7 Plan method of monitoring lighting conditions during experimentation to assure variations due to unpredicted circumstances or time-variable factors (line voltage fluctuations, lamp output variations) are detected.

C3.6.8 Develop intermediate report. Obtain review by outside specialist group. Modify per comments and suggestions received.

C3.7 Select Experimental Test Subjects.

3.7.1 Address driver characteristics. Develop requirements of test subjects (age, sex, eyesight) and number of persons required as subjects. Particular attention should be given to driver age to ensure that variations in driver performance that may be related to age are addressed.

C4. IMPLEMENTATION

C4.1 Measure vision and ocular conditions relevant to night driving for all subjects, including yellowing of the eye lens.

C4.2 Conduct Experiments

C4.2.1 Collect data from all variable combinations. Data should be stored using Microsoft Excel software.

C4.2.2 Analyze raw data to assure results that are significant at a 95% confidence level. If appropriate, modify test procedure and redo experiment, or conduct additional trials.

C4.3 Analyze and Report Results

C4.3.1 Analyze test results and report. Conduct concurrently with experiments rather than delay until all data have been collected. (Interim results may indicate advisability of modifying the research program.) Use statistical tests to determine reliability of results.

C4.3.2 Balance any positive and negative effects on safety against relevant accident types and frequencies. A large positive effect on one infrequent accident type may be offset by a small negative effect on a more frequent accident type.

C4.3.3 Develop life-cycle cost data for the lighting systems used.

C4.3.4 Write research paper detailing findings in accordance with Arizona Transportation Research Center guidelines. Note: major input will be required from ADOT, as the research team is not likely to be able to resolve anticipated trade-offs between safety and costs.

C4.3.4 Develop draft final report. Submit to outside specialist group. Incorporate comments and suggestions received.

C4.3.5 Submit report for review to ADOT or cognizant authority.

C4.3.6 Modify report per ADOT requirements and issue final report.

C5. ALTERNATIVE RESEARCH PLANS

The foregoing has outlined a complete plan to investigate the various factors of interest. It is recognized, however, that funding limitations may restrict the extent of the work. Under such conditions the work may be accomplished in stages, with the various steps being completed as the funding allows. A summary of the work effort broken into stages is provided below.

C5.1 Stage 1 Work Plan

Referenced to the earlier section 3 of this research plan, stage 1 work would include:

> Driver visual tasks, (section3.1). This is the fundamental basis and is required even for a limited study. Potentially, visits to other facilities could be limited, but this is not recommended as the information transfer and consequent cost savings may be substantial.
>
> Lighting system specifications, (section 3.2). Reduce the scope of this effort by simplifying the range of geometries that will be investigated. Eliminate consideration of moving poles, changing mounting heights and altering mast arm lengths. Focus on testing that can be accomplished using existing fixed facilities. The effort must retain the ability to investigate different lamp types, and should provide variable lighting level through dimming.
>
> Acquisition of Test Facility and Luminaires, (section 3.3). This effort will be simplified as lighting geometry variation has been reduced or eliminated.
>
> Luminaire Evaluations, (section 3.4). This effort is essential and will be retained.
>
> Driver Response, (section 3.5). Also essential for any research effort.
>
> Experimental Design, (section 3.6). Develop a limited range of experiments. Restrict the testing to two lighting levels only. Use the three lamp types with a single geometry. (Installation design should be as similar as possible for all three, within the constraints caused by the lamp characteristics). Limit testing to conditions without opposing headlamps. As per sections 3.6.5 and 3.6.6, develop methodology for analysis of results and randomness of testing.
>
> Select subjects. Perform as per section 3.7.1.

Implementation will be as section 4 above, but the extent of the tasks will be substantially reduced.

C5.2 Stage 2 Work Plan

Stage 2 will conduct further experiments using the same lighting system geometries as used in Stage 1. Additional testing will include:

Testing under the full range of lighting levels as developed in the project planning, (section 3.2.1), including the zero roadway lighting level condition. Additional testing will be conducted under conditions of oncoming headlamp glare.

Stage 2 will add considerable data to that obtained during Stage 1, providing a full test data matrix, but limited to a single geometry.

C5.3 Stage 3 Work Plan

Stage 3 will require upgrading of the test facilities to allow for variable lighting system geometry per section 3.2 above. This will provide the complete range of lighting parameters, such as is necessary for the investigation of lighting systems as used on a wide variety of roadway types.

Test data then will be collected in the same manner as stages 1 and 2, but for the full range of lighting conditions. Completion of stage 3 will provide the full data envisaged for the project as described in sections 3 and 4 above.

C6. RESEARCH FUNDING

The estimated cost for conducting the research detailed in sections C3 and C4 is shown in Table C1. Estimates are based on a cost of $130 per hour for a research engineer and $90 per hour for a research assistant.

Additional costs will be incurred for payments to test subjects. Estimated at $20 per hour, these costs are:

Single project.	Test subject payments = $64,000
Stage 1	Test subject payments = $16,000
Stage 2	Test subject payments = $22,000
Stage 3	Test subject payments = $32,000
	$70,000

Total costs based on Table C1 and the above are:

	Single project.	Total estimates costs = $692,130
Or:	Stage 1	Total estimates costs = $261,500
	Stage 2	Total estimates costs = $166,250

Stage 3	Total estimates costs = $315,590
Total for 3 stages:	$743,340

Capital costs associated with providing the test facility are not included in the above figures.

C7. POTENTIAL RESEARCH PARTNERSHIPS

C7.1 FHWA is reported to have funds available for lighting-related research, and ADOT-FHWA sponsorship should be considered.

C7.2 AASHTO/NCHRP has funded prior lighting research projects, as proposed by states. Given the universal applicability of the work, AASHTO/NCHRP sponsorship could be available for the project.

C7.3 Local counties and/or municipalities might participate by making traffic volume and/or accident reports available.

C8. PROGRAM DURATION

Research duration is estimated as 24 months, exclusive of test track construction.

TABLE C1 – COST AND MAN HOURS ESTIMATE

Estimated Man-hours	Single Project				Stage 1		Stage 2		Stage 3		Three Stages	
	(Engineer)	Engineering Assistant	Total (per task)	Labor $	Engineer	Engineering Assistant	Engineer	Engineering Assistant	Engineer	Engineering Assistant	Total per task	Labor $
Task:												
3.1 Driver Visual Tasks												
3.1.1	60		60	7,800	60						60	7,800
3.1.2	80		80	10,400	80						80	10,400
3.1.3	20		20	2,600	20						20	2,600
3.1.4	50		50	6,500	50						50	6,500
3.1.5	30		30	3,900	30						30	3,900
3.2 Lighting System												
Specifications												
3.2.1	20		20	2,600	20						20	2,600
3.2.2	100		100	13,000	40				80		120	15,600
3.2.3	20		20	2,600	20						20	2,600
3.2.4	20		20	2,600	10				15		25	3,250
3.3 Acquisition of Test	40		40	5,200	30				20		50	6,500
Facility and Luminaires												
3.4 Luminaire Evaluations												
3.4.1	20	250	270	25,100	20	250					270	25,100
3.4.2	10	4	14	1,660	10	4			5		19	2,310
3.4.3	40		40	5,200	20				30		50	6,500
3.4.4	50	40	90	10,100	20	20	10	10	30	30	120	13,200
3.4.5	4	60	64	5,920	4	60					64	5,920
3.5 Driver Response												
3.5.1	30		30	3,900	30						30	3,900

TABLE C1 – COST AND MAN HOURS ESTIMATE

3.5.2	30	50	80	8,400	30	50					80	8,400
3.6 Experimental Design												
3.6.1	25		25	3,250	25						25	3,250
3.6.2	4		4	520	4						4	520
3.6.3	4		4	520			4				4	520
3.6.4	40		40	5,200	22		21		21		64	8,320
3.6.5	40		40	5,200	40						40	5,200
3.6.6	20		20	2,600	15		5		5		25	3,250
3.6.7	8	8	16	1,760	8	8					16	1,760
3.6.8	24		24	3,120			15		12		27	3,510
3.7 Select Experimental	20		20	2,600	20						20	2,600
Test Subject												
4.1 Eye Testing	6		6	780	6						6	780
4.2 Conduct Experiments	2200	1100	3300	385,000	450	250	600	300	1250	625	3475	404,750
4.3 Analyze and Report												
Results												
4.3.1	350		350	45,500	100		120		140		360	46,800
4.3.2	40		40	5,200	20		20		20		60	7,800
4.3.3	40		40	5,200	20		20		20		60	7,800
4.3.4												
4.3.5	40		40	5,200	20		20		20		60	7,800
4.3.6												
Project Management	300		300	39,000	200		60		60		320	41,600
Totals	3785	1512	5297	628,130	1444	642	895	310	1728	655	5674	673,340

APPENDIX D

RESEARCH PLAN FOR THE FIELD STUDY OF LIGHT SOURCE TYPES AS RELATED TO ACCIDENTS

Reference: Research Topic SPR 522-2

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April 2003

APPENDIX D

RESEARCH PLAN FOR THE FIELD STUDY OF LIGHT SOURCE TYPE AS RELATED TO ACCIDENTS

D1. PROBLEM STATEMENT

D1.1 Roadway lighting provides increased safety at night by providing better visibility. Factors involved in roadway lighting include effectiveness, life-cycle cost, light pollution and trespass, and object recognition.

D1.2 Light source type has previously been related to economic factors such as lamp lumen output, lumen depreciation, maintenance, lamp life and fixture cost. However, evidence now suggests that different light sources may affect the visibility created, and therefore may influence safety. The different spectral characteristics of the various light sources may be the dependent variable.

D1.3 Comparisons of light source spectral distributions as related to visibility have been carried out under laboratory conditions. However, no field studies have been conducted to determine whether the visibility characteristics found in the laboratory will affect safety in actual field applications. Through laboratory experiments several factors, including lighting level and the nature of visual task, have been shown to influence visibility. However, the extent of their impact in the field is not fully understood.

D1.4 A study is needed to determine if there is a relationship between spectral light source characteristics and nighttime safety. The three different sources proposed for study are high pressure sodium (HPS), low pressure sodium (LPS), and metal halide (MH).

D1.5 Different visual tasks have varying significance for different roadways. For example, peripheral tasks may be more important in a major suburban roadway than for a limited access highway. It is further recognized that the types of accidents will vary by roadway type. A full study of lamp spectral effects therefore requires consideration of various roadway types. This study is likely to be limited to one particular roadway type because of limited availability of suitable test sites and funding.

D2. RESEARCH OBJECTIVES

The objective of this program is to look for a correlation between nighttime crash rates and light sources. The proposed research will install the three types of lighting (HPS, LPS and MH) on roadways with similar physical characteristics and usage patterns. The aim is to achieve the objectives with modest research funding.

D3. RESEARCH TASKS

D3.1 Select a route with the following characteristics: a) consistent cross-section geometry; b) uniform traffic volume and composition; c) high level of abutting land use (high volumes of pedestrian and entering/exiting/turning vehicular activity); and d) long enough to be divided into three sections having a total of 400 reported crashes over the expected time period of the research (see Section D4.1.1).

D3.2 Design and install the three types of lighting systems along the roadway. After installation, verify that the lighting levels are as designed.

D3.3 Collect and analyze traffic volumes and crash reports.

D3.4 Write research paper detailing findings in accordance with Arizona Transportation Research Center guidelines.

D4. SITE REQUIREMENTS

D4.1 For safety studies to achieve statistical significance there must be a large number of crashes studied. These are related to the following three elements: traffic volume, length of roadway section, and length of study period. Initially it is estimated that the roadway section lengths will be a minimum of five miles in order to gather the necessary data.

D4.1.1 Number of Accidents

For a “Before-and-After” improvement study’s findings to be significant, there needs to be a crash sample of 100 for the starting condition (HPS lighting). There then needs to be a difference of 16 crashes (plus or minus) in the comparative light sources (LPS and MH) to be significant at a Poisson distribution 95% confidence level or a difference of 25 crashes (plus or minus) for the more conservative Chi-square test[1]. The nighttime traffic volume is approximately twenty-five percent (25%) of the total daily volume[2,3] and well lit urban and suburban routes have approximately twenty-three percent (23%) of their crashes at night. Therefore, a minimum of 400 total crashes are needed to generate the 100 nighttime crashes.

D4.1.2 Duration of Study

The estimated study period is thirty six months. This study length allows for a “regression to the mean” analysis of the collected data. A longer study period may be needed to generate sufficient data to provide statistically significant findings.

D4.1.3 Type of Study

A primary factor related to lamp spectral distribution is peripheral vision object detection, and therefore routes with pedestrians, bicycles, frequent driveways and cross streets are likely to show the greatest change with lamp type. Routes with rural land use have little entering conflict from the roadside, apart from animals. Similarly, freeways present few peripheral entry conflicts, and mesopic spectral effects are likely to be minimized. The research program should address this issue by recognizing the impact of selected test site.

D4.1.4 Other Route Characteristics

In addition to the roadway characteristics detailed in Section D3.1.1, routes with existing overhead power lines present an advantage. Easily accessible electricity minimizes construction costs and time. It also facilitates changing pole spacing as a research variable.

D5. IMPLEMENTATION

D5.1 Several types of study sites along with their advantages and disadvantages are shown below.

D5.1.1 Use of Existing Freeways

An existing, lighted freeway would be divided into three sections based on traffic volumes and length. Each section would be lit at equivalent levels using the three types of lighting sources under review.

Advantages: a) high traffic volumes; and b) if Loop 101 is chosen, reduction in cost as HPS lighting is already installed and could be used on one section;

Disadvantages: a) freeways do not have any pedestrian conflicts nor significant numbers of side conflicts; and b) if Loop 101 is chosen, the existing light poles would have to be relocated/replaced to provide for equivalent lighting levels using LPS and MH light sources.

D5.1.2 Use of an Unlit Freeway

Either an existing, unlit freeway or a new freeway would be divided into three sections and lit with the three types of light sources.

Advantages: a) high traffic volumes; and b) no removal of existing facilities prior to installation of test lighting.

Disadvantages: a) freeways do not have any pedestrian conflicts nor significant numbers of side conflicts; and b) additional cost to light one section with HPS.

D5.1.3 Use of an Unlit Major Arterial Roadway

An unlit major arterial (SR 87, McDowell Road to Ft. McDowell Road; US 60 west of Van Buren St.; or SR 89 through Flagstaff.)

SR 87:
Advantages: a) consistent roadway cross-section; b) large volume of traffic; and c) accessible overhead electric power.

Disadvantage: a) extremely low volume of turning, entering, and exiting traffic; and b) total lack of pedestrian traffic.

US 60, west of Camelback Road:

Advantage: existing LPS lighting from Camelback Road to Northern Avenue is easily upgradable to test levels for this research.

Disadvantages: roadway cross-section west of Northern Avenue are different, thus introducing another variable; and b) the abutting land use to the west is industrial with low volumes of pedestrian traffic and a minimal number of conflicting movements.

SR 89 Through Flagstaff:
Advantages: a) existing LPS lighting; b) high traffic and conflicting movement volumes; c) high volume of pedestrian activity; and d) consistent roadway cross-section.

Disadvantages: a) the section through Flagstaff is relatively short; b) vehicle speeds are low; c) the section is heavily signaled, which minimizes turning movement conflicts; and d) the use of HPS and MH lighting is discouraged within the City limits.

Possible Alternatives: identify and evaluate alternate, potential sites outside of the Phoenix metropolitan area.

D5.1.4 Need for Site Search.

Other cities such as Tucson and Yuma should be searched for potential routes. Another potential would be lighting county or city major routes that are being improved in newly developing parts of the Phoenix metro area. The disadvantage of such a selection would be the rapid increase in conflict activity as the new area development proceeds. This could invalidate the results of multi-year analysis to reduce regression to the mean problems.

The study sections will each require traffic volume data to be made available. A permanent counter station with hourly counts for a full year is not essential, if the 25% night value found in numerous other studies is accepted.

Hard-copy accident reports will be essential to the analysis, in order to assess the entry of conflicting elements first detectable in peripheral vision. Reports of <u>all</u> accidents reported to the police are highly desirable; not just the ones with a personal injury or State-reportable \$1,000 property damage limit.

It is recognized that the selection of the site is likely to be influenced by convenience and availability, and that ideal locations may not be obtained.

D6. SPECIFICATION OF EQUIPMENT

Develop complete set of contract documents, signed and sealed, for the installation of the roadway lighting test sections.

D7. DATA COLLECTION, TABULATION AND ANALYSIS

Collect and tabulate, on an annual basis, all crash reports. Analyze reports to adjust length of study to produce significant results. Compile, tabulate, and analyze data at project end.

D8. RESEARCH REPORT

The project research report shall be in accordance with the Arizona Transportation Research Center guidelines and contain the following elements.

D8.1 Describe the criteria used in study site selection.

D8.2 Describe and illustrate the following existing roadway conditions at a minimum: a) roadway cross-sections; b) abutting land use; c) traffic volume and composition; d) posted speed and average running speed; e) intersections and driveway frequency; f) study section lengths; and g) volume of pedestrian traffic.

D8.3 Detailed in detail the lighting systems used on each segment of the test roadway. The comparison of modeled vs. field lighting values should be reported.

D8.4 Detail the life-cycle costs of the three lighting systems.

D8.5 Present crash data, including the following: a) number; b) type; and c) relevance to peripheral vision tasks. Calculate the statistical significance confidence level.

D8.6 Suggest further research as appropriate.

D9. RESEARCH FUNDING

The estimated cost for conducting the research is shown in Table 1. This does not include the cost of providing the infrastructure for the three lighting types.

TABLE D1. ESTIMATED MAN-HOURS AND COSTS

Reference Section		Engineer	Engineering Assistant	Cost
3.1.1	Site Selection	80	10	$11,300
3.1.2	Design and Implementation	90	30	$14,400
3.1.3	Annual Data Collection (2 years)	200	20	$27,800
3.1.4	Summary Report	40	20	$7,000
Misc.	Meetings and Project Management	80		$10,400
Total		490	80	
Cost	Costs are based on an hourly rate of $130 for an engineer and $90 for an engineer assistant.	$63,700	$7,200	$70,900

Traffic Engineering and Roadway Design are the critical ADOT sections that may support this effort. These also are the ADOT sections that primarily will benefit from the research program.

D10. POTENTIAL PARTNERSHIPS

D10.1 FHWA is reported to have funds available for lighting-related research, and ADOT-FHWA sponsorship should be considered.

D10.2 NCHRP has funded prior lighting research projects, as proposed by states. Given the universal applicability of the work, NCHRP sponsorship could be available for the project.

D10.3 Local counties and/or municipalities might participate by making traffic volume and/or accident reports available.

D11. RESEARCH DURATION

Research duration is estimated as 36 months, exclusive of lighting systems installation.

REFERENCES

1. Michaels, Richard M., Two Simple Techniques for Determining Significance of Accident Reducing Measures, Traffic Engineering, Sept. 1966.

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3. McCoy, P.T., J.A. Bonneson, et al; Guidelines for Right-Turn Lanes on Urban Roadways, Transportation Research Board annual meeting, 9-13 January 1994.

4. Box, Paul C.; Major Road Accident Reduction by Illumination, Transportation Research Record 1247, Transportation Research Board, 1990.

5. American National Standard Practice for Roadway Lighting, ANSI/IESNA RP-8-00, Illuminating Engineering Society, 2000.