Deck Park Tunnel Energy Efficiency Study

Final Report

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I. Project Introduction

The scope of this project was to evaluate the energy consumption of the existing lighting and the fans serving the Deck Park, I-10 Tunnel in Phoenix, Arizona. By analyzing the equipment, light fixtures, operational cycles and energy consumption, we were able evaluate options for making the system more energy efficient.

This report will cover the energy efficiency assessments for the ventilation and lighting systems and will highlight current systems as well as potential energy saving strategies.

II. Mechanical Assessment

a. Introduction

Ventilation is one of the most critical components to the design and operation of a vehicular tunnel. It not only affects the electrical consumption of the system but is the critical component of safety during normal day to day operation an especially during accidents or fires within the tunnel itself.

The scope of our evaluation was only related to reduction in energy usage by fans rather than general evaluation of the overall ventilation system.

Our objective for the study was to investigate any modifications required for the fans in order to improve the energy efficiency and provide a positive payback.

b. Existing Conditions:

The Deck Park Tunnel in Phoenix, Arizona consists of two directional tunnels, one east-bound and one west-bound. The tunnel is approximately 2,887 feet long. The mechanical system serves the tunnel through longitudinal ventilation. The ventilation injects air or removes air from tunnel at number of points overhead along its length based on the mode of operation.

Each tunnel is served by four large 2-speed vaneaxial fans. Each fan operates at 4160V, 3-phase, and 250hp at low speed and 700hp at high speed. The fans are rated to operate at approximately 41A at low speed and 95A at high speed. A maximum of eight fans can operate at any given time.

There are total of six CO (carbon monoxide) sensors installed in each tunnel. Two at the entrance to the tunnel, two at mid-level and two close to the tunnel exit. The CO sensors measure the CO level in the tunnel and energize the fans as required to maintain proper CO levels in the tunnel. The set point of these sensors is 35 PPM.

The ventilation system is designed to accommodate normal, congested and emergency modes of operation.

Normal Mode: in this mode of operation all fans are off. During this mode of operations vehicles are moving through the tunnel at a speed which induces natural airflow through the tunnel which is adequate to maintain CO level within the guidelines.

Congested Mode: In this mode of operation, due to vehicular traffic and relatively slower speed, the tunnel will require mechanical ventilation. During this mode of operation CO sensors energize the first stage of the supply fans. As the CO levels exceed above the set point the next set of the supply fans will be energized. In total, four exhaust fans will provide the ventilation for each tunnel.

Emergency Mode: This mode of operation is determined by the operator. Based on the condition of the emergency, the fans can be started and the flow of air in the tunnel can be reversed and exhausted. During this mode of operation fans will be operating at maximum speed.

c. System Energy Evaluation:

To evaluate the potential energy reduction, it was essential to determine energy usage by these fans. We conducted testing of the fans to determine their energy consumption at low and high speed. Results of this test have been recorded below. All eight fans are normally off. Predominantly when the fans are on, they are operating in low speed. They operate in high speed during flow reversal and emergency situations which are statistically very rare.

These conditions vary day to day and are not predictable. In order to establish trending and usage data, ADOT provided us with information as to the amount of hours that the fans have operated over a three year period of time, illustrated below.

FAN	DIRECTION	HOURS OF OPERATION
1A	Westbound	3122
1B	Westbound	2548
2A	Westbound	3018
2B	Westbound	3189
3A	Eastbound	1028
3B	Eastbound	1013
4A	Eastbound	997
4B	Eastbound	942

To determine the actual amp draw for the fans we conducted an analysis for two fans in one of the vent rooms and established an average to use for our calculations. The following table shows the actual demand readings taken from the control room computer.

FAN	SPEED	AMPS
3A	Low	8.6
3A	High	90.6
3B	Low	7.7
3B	High	87.5
AVERAGE	**LOW**	**8.2**
AVERAGE	**HIGH**	**89.1**

From that information and the nameplate data, we calculated the average power factor (pf).

95A x 4160V x 1.732050808 = 684,506VA

684,506VA x pf = Watts, therefore pf = watts / volt-amps

$\frac{\text{Kilowatts}}{\text{700hp}} = \frac{0.74569}{1}$ therefore 700hp fan = 521.983kW or 521,983 watts

$\frac{\text{521,983 W}}{\text{684,506 VA}}$ = **pf = 0.7626**

After calculating the power factor, we established the average operating wattages for each fan.

SPEED	AVERAGE AMPS	POWER FACTOR	VOLTAGE	AVERAGE WATTAGE	KW
Low	8.2	0.7626	4160-3PHASE	45,057	45.057
High	89.1	0.7626	4160-3PHASE	489,585	489.585

Nameplate data for the fans are 186kW in low speed and 522kW in high speed. Actual values from table above were used to establish approximate cost of fan operation.

d. Cost Assessment

ADOT supplied ESD with their electrical bills for the last year and from those we calculated the average electrical cost to be $0.087 per KWh. Taking the hours of operation from the table above and the average wattage for a fan in low speed, we were able to calculate the total cost for fan operation over the last 3 years to establish the impact of the fan operation as it relates to the overall energy consumption of the tunnel. Table below illustrates cost of fans.

FAN	HOURS OF OPERATION	AVERAGE FAN WATTAGE (KW)	COST PER KWH	TOTAL COST
1A	**3122**	45.057	$0.087	$12,238
1B	**2548**	45.057	$0.087	$ 9,988
2A	**3018**	45.057	$0.087	$11,830
2B	**3189**	45.057	$0.087	$12,501
3A	**1028**	45.057	$0.087	$ 4,030
3B	**1013**	45.057	$0.087	$ 3,971
4A	**997**	45.057	$0.087	$ 3,908
4B	**942**	45.057	$0.087	$ 3,693

The total cost for all fans shown above is $62,159 over three years. Divided by three, that is approximately $20,719 per year in operation cost. According to ADOT records, the annual electricity cost is approximately $368,443. Per our calculations, the eight fans account for about 6% of the electricity required to operate the tunnels.

e. Energy Efficient Improvements

The eight fans were custom built for this tunnel application by TLT Babcock. The fans themselves were rebuilt between 2007 and 2008. In order to determine whether or not there were options to make the current system more energy efficient, we contacted TLT Babcock regarding the option to make the 2-speed fans variable speed, by adding VFD's (variable frequency drives).

As designed, the system it does not lend itself to a variable frequency drive (VFD) application. The motors are designed and rated for two speed operation with a sophisticated control for reversing the airflow.

Also, the installation of 4160 VFD is very costly. We have contacted an ABB representative, a manufacturer and specialist of VFD's. They suggested the replacement of the motors and the addition of a 4160 to 480 transformer instead of providing medium voltage VFD.

It is not feasible at this time to re-build fans for variable speed operation. Based on our assessment, the fans are operating in an efficient manner.

III. Lighting Assessment

a. Executive Summary

The purpose of this lighting assessment was to first perform a detailed evaluation of the existing tunnel lighting and lighting controls systems, and then to develop options for improving the energy-efficiency of these systems, while maintaining or improving the quality of the illumination. The primary findings of the evaluation are that:

- The existing luminance levels in the Threshold Zones are much lower than the levels included in the original design documents.
- The existing luminance levels in all zones are lower than those included in the current "recommended practices" developed by the IESNA and CIE.
- Performing the IESNA/CIE-suggested Lseq analysis determined that the Deck Park Tunnel and its surroundings comprise a very unique application, which resulted in the L_{SEQ} analysis recommending extremely high luminance levels in the Threshold Zones. As these recommended Threshold Luminance levels (L_{TH}) were substantially higher than any levels incorporated into actual past projects designed by the Lighting Team members, ADOT chose to select two other, more reasonable levels (250 & 350 cd/m^2) to utilize as analysis targets for the purposes of this evaluation.

The following table summarizes: luminance calculations that were included in the Original Design Documents, the Calculated Existing luminance levels that were determined as part of this study and were Field Verified by representative measurements, and the Target L_{TH} levels of *250* and *350* cd/m^2 as Selected by ADOT. The other luminance values in the last two columns are estimates of what those values would be if the designs were to be prepared in accordance with RP-22-11.

Average Luminance Levels Throughout The Tunnel (cd/m^2) (Table 1)

Tunnel Zone (section)	Original Design Documents (MF = 0.69)		Calculated Existing and Field Verified		Target L_{TH} of *250* Selected by ADOT		Target L_{TH} of *350* Selected by ADOT	
	Day	Night	Day	Night	Day	Night	Day	Night
Threshold Zone	287	N/P	110	1.4	*250*	2.5	*350*	2.5
Threshold Zone 2nd Half	N/A	N/A	N/A	N/A	175	2.5	245	2.5
Transition Zone 1	33	N/P	26	1.5	69	2.5	96	2.5
Transition Zone 2	N/P	N/P	7.9	2.7	28	2.5	39	2.5
Transition Zone 3	N/P	N/P	7.4	2.4	17	2.5	24	2.5
Interior Zone	6.3	3.2	6.9	2.1	11	2.5	11	2.5

In the preceding table:

- "N/A" means that this information is "not applicable", as the zone titled "Threshold Zone 2nd Half" did not exist at the time that the tunnel was originally designed.
- "N/P" means that this information was "not provided" in the original design documents

Before ADOT can pursue any of the Options contained in this report, it first needs to determine whether or not the tunnel illumination needs to be upgraded so that it conforms to modern IESNA/CIE design practice – particularly in regards to the luminance levels in the Threshold Zones. When contemplating the major renovation of an aging transportation project, consideration should always be given to upgrading the lighting so that it conforms to modern design practices ("recommended practices"), as this will provide benefits in regards to functionality, maintenance, liability, and energy-efficiency. In addition to upgrading the "normal" lighting, the renovation should also address the "emergency" lighting, as there have been several revisions to the NEC and NFPA codes since the tunnel was completed.

In the event that ADOT is satisfied with the existing luminance levels; then it is possible to save energy by implementing Options 2, 3, 4, 5, 6 & 7, as each one either proposes a method for achieving a reduction in the amount of electric lighting needed in a particular zone, or a method for generating that same amount of lighting in a more energy-efficient fashion. Implementing all of the Options could result in a potential overall energy savings of approximately 70%.

In the event that ADOT decides to increase the luminance levels; then it is unlikely that ADOT will be able to achieve any energy savings as compared to the existing energy costs, as all of the efficiencies generated by the implemented Options will go toward utilizing the same amount of energy consumption to generate higher luminance levels. Under this scenario, it would be possible to increase the L_{TH} to as much as approximately 200 cd/m^2.

Unless ADOT decides to implement "Option 3", which recommends the installation of an exterior Shade Structure, achieving the target L_{TH} levels of 250 or 350 cd/m^2 will require the installation of additional luminaires and wattage, which will in turn require upgrades to the tunnel's electrical infrastructure. In the case of an L_{TH} equal to 250 cd/m2, the additional lighting load would require adding capacity to the electrical panels located in the ventilation rooms. In the case of an L_{TH} equal to 350 cd/m^2 or higher, the additional lighting load would require a substantial upgrade to all of the tunnel's electrical infrastructure, including the main section and utility transformers. Therefore, ADOT should consider the implementation of Option 3 as the most energy-efficient method by which to achieve high L_{TH} levels, and conformance with modern design practices.

b. Introduction and Basics of Tunnel Lighting

The evaluation process included reviewing the construction documents, two data-gathering visits to the control room & electrical/vent rooms, and three lengthy walk-throughs of both tunnels/tubes during partial & full closures. In addition to gathering data on the equipment, these walk-throughs included evaluations of the various surfaces within the tunnel, physical measurements of the various ceiling heights, and representative illuminance and luminance measurements.

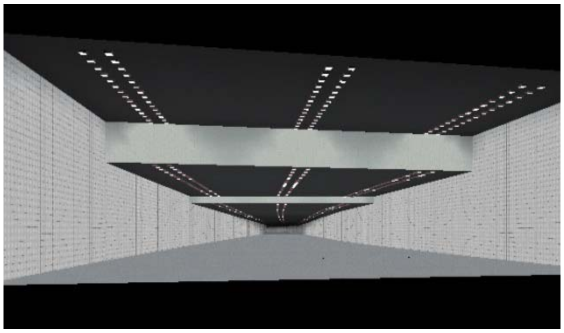
Utilizing the original construction documents, other data and reports supplied by ADOT, as well as the data gathered during the field evaluation process, it was then possible to create a complete 3-D CAD file for each tunnel/tube, which included the tunnel shape & dimensions, luminaire types & locations, and identification of the electrical circuits & lighting control zones. In addition to utilizing the CAD files for our evaluation, these files were also distributed to several lighting equipment manufacturers so that they could prepare detailed submittals with proposed luminaire types and locations.

These CAD files were then utilized as the background for creating the computer simulations of the existing lighting conditions, as well as for the proposed upgrade options. Extremely detailed photometric studies and renderings were created in a software package known as AGi32 version 2.2, which is capable of highly accurate photometric analysis & 3-D rendering, and it is considered to be the standard for analysis software in the lighting industry. *(See Attachment #1)*

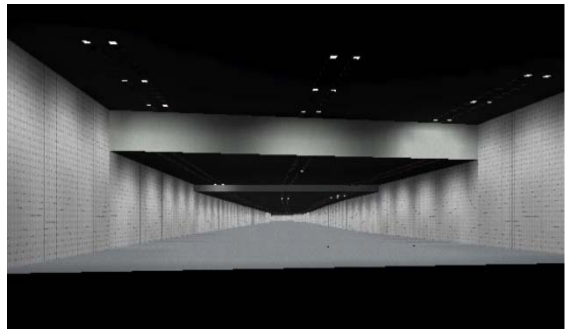
The first simulation of an operating scenario to be created was designated as the "Existing Base Case", which represented the current lighting conditions in the tunnel, and was to be utilized as the base case against which all proposed upgrade options were to be compared. This simulation was fine-tuned so that the detailed results closely matched the actual illuminance & luminance measurements that were gathered during the tunnel closures. Upon finalization of an accurate base case simulation/analysis, it was then possible to prepare additional simulations/analyses for the various proposed upgrade options that are detailed in this report.

The CAD and AGI files have been provided on a flash-drive storage device that can be found in the Appendices. The manufacturer submittals have been included as well, in their entirety, and unedited.

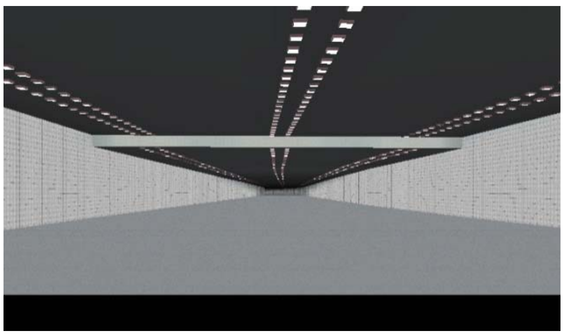
Still images generated by AGi32



Eastbound Threshold Zone
All Lights On

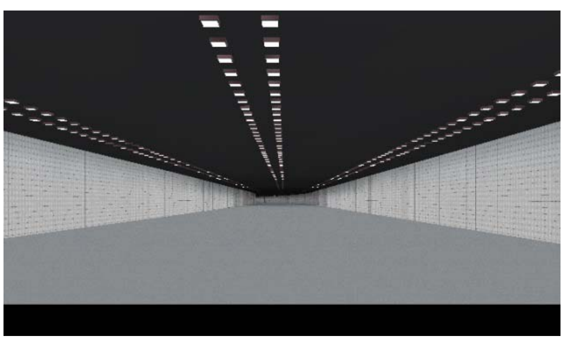


Eastbound Threshold Zone
Nighttime Mode

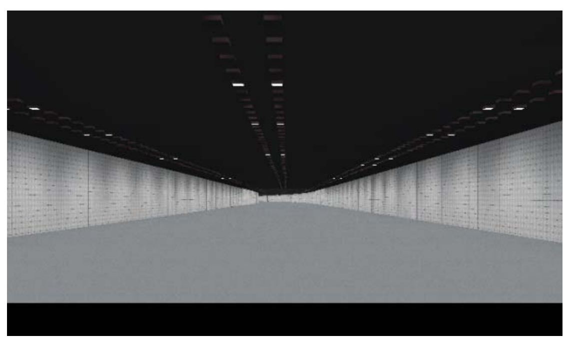


Eastbound Transition Zone 1
All Lights On

Eastbound Transition Zone 1
Nighttime Mode



Eastbound Interior Zone
All Lights On



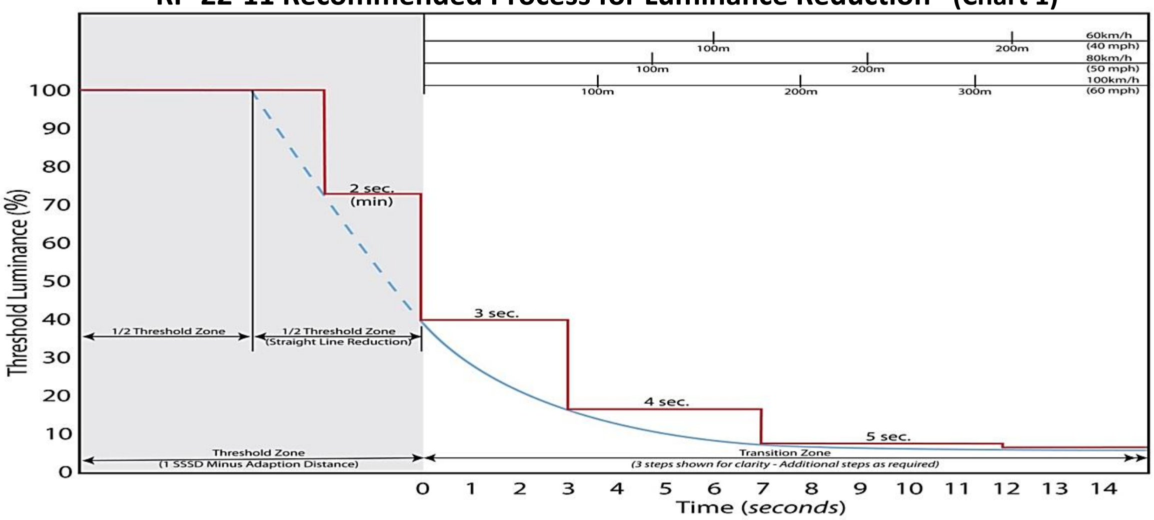
Eastbound Interior Zone
Nighttime Mode

Basics of Tunnel Lighting

Tunnel lighting is unique among lighting applications in that the quantity of necessary illumination changes from one end of the project to the other, differs depending upon the speed of the traffic and the location/orientation of the project, and is constantly changing in proportion to the level of ambient daylight. The lighting system must therefore be flexible, and designed to properly manage the transient adaptation of the driver's vision over the varying visibility conditions that naturally occur outdoors.

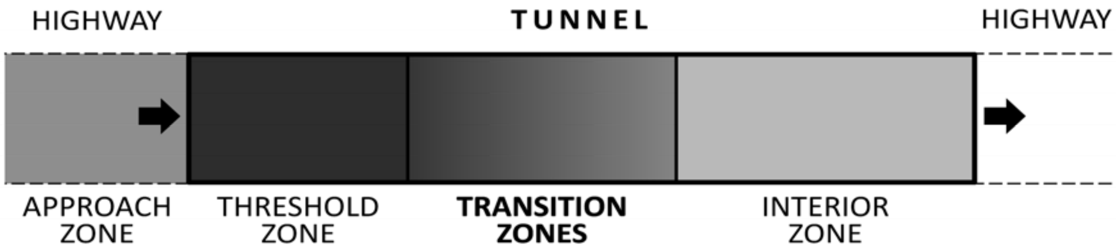
Recommended design practices for tunnel lighting systems in North America are detailed in a document titled "RP-22 Recommended Practice for Tunnel Lighting" that is published by the Illuminating Engineering Society of North America (IESNA). The 2011 version of this document, for the first time, creates a bridge between the IESNA documents utilized in North America, and the International Commission on Illumination (CIE) documents utilized in Europe. The following image, which details the lengths of the various lighting "zones" and associated lighting levels found within a tunnel, appears in both a CIE document from 2004, and the 2011 version of the RP-22.

RP-22-11 Recommended Process for Luminance Reduction (Chart 1)



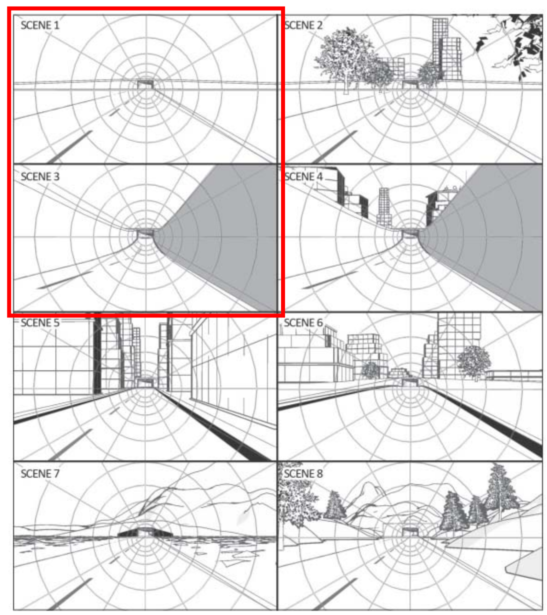
Recommended Luminance Reduction for Threshold and Transition Zones
(Adapted from CIE 88 2004, **Figure 6.62**)

Most tunnel illumination can be divided into three general types of lighting zones: Threshold, Transition, and Interior. The Threshold zone is located immediately within the tunnel entrance, and is the most brightly illuminated, as it must attempt to minimize the amount of adaptation required for a driver's eye to deal with the abrupt transition between bright daylight outdoors and the electric lighting inside the tunnel. The Interior zone comprises roughly the second half of the tunnel, and is the only zone for which there are set illumination standards – even though the recommended luminance standards are different for daytime versus nighttime operation. The Transition zones are located between the Threshold Zone and Interior Zone, and are designed to provide a gradual reduction in lighting levels between those two zones so that the average driver will have time for their vision to adapt to the lower illumination level found throughout the Interior Zone.



Whereas there are a pre-determined set of recommended minimum illumination levels for the Interior Zone, the amount of illumination required for the Threshold is extremely variable, and must be determined for each tunnel project. This variability has an indirect and dramatic effect upon the lighting in the Transition zones, as the amount of lighting in those zones must be increased in proportion to whatever amount of lighting is determined to be necessary for the Threshold zone.

ANSI/IES RP-22-11 provides a table method for the determination of the expected required threshold lighting luminance (L_{TH}) at a tunnel based on driver direction, general approach conditions, and the posted speed of the approach roadway. This method of determining the L_{TH} is only used for preliminary design and provides a general estimate of the needed luminance values. The I-10 Deck Park Tunnel has a driver direction of east/west, a portal configuration that most closely matches **Scene 1 or 2** in the adjacent image, and a posted speed limit of 65 mph. Based upon these conditions, and using linear interpolation, the preliminary estimate for the threshold lighting level (L_{TH}) would be approximately 335 cd/m^2. This lighting level would be expected to provide sufficient illumination at the beginning of the tunnel to identify hazards or stopped vehicles inside the tunnel by motorists approaching the tunnel at a sufficient distance to be able to make a safe stop.

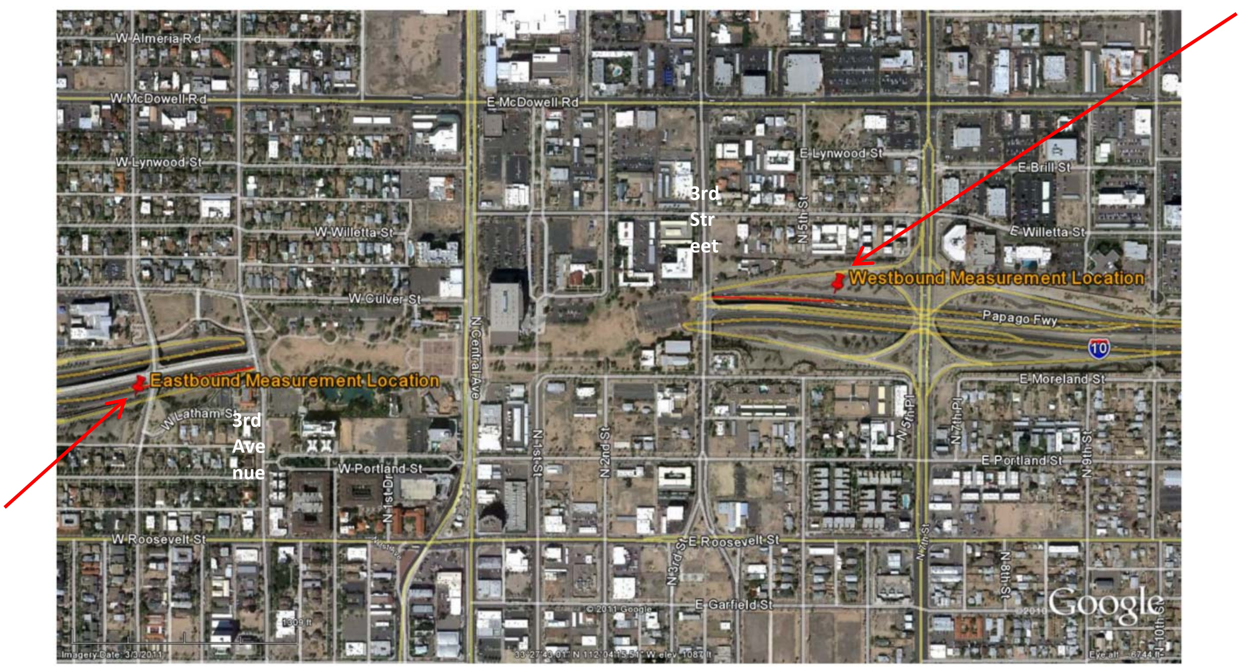


(Table 3) **Suggested Daytime Maintained Average Pavement Luminance Levels in the Threshold Zone of Vehicular Tunnels (Lth)**

Approach Characteristics	Traffic Speed		Driver Direction		
	km/h	mph	North	East-West	South
			cd/m²		
Open Road Scene 1,2,3	100 80 60	60 50 40	250 220 180	310 260 220	370 320 270
Urban Tunnel Scene 4,5,6	100 80 60	60 50 40	320 280 230	280 240 200	310 270 220
Mountain Tunnel Scene 7,8	100 80 60	60 50 40	230 200 170	200 170 140	200 170 140

RP-22-11 recommends that, if possible, equivalent veiling luminance (Lseq) luminance measurements should be performed at several different times over the course of a day, in order to quantify the varying levels of outdoor ambient daylight, with which the lighting in the Threshold and Transition Zones will have to contend. It was therefore decided to perform the measurement on an hourly basis, and for both the eastbound and westbound thresholds. These hourly luminance measurements were performed on June 11, 2011, utilizing ADOT's own luminance meter and specialized Fry lens.

As these luminance (brightness) measurements are intended to simulate how the tunnel portal "appears" to the human eye, the measurements are performed at a distance of one AASHTO "Safe Stopping Sight Distance" (SSSD) from the tunnel portal. One SSSD is equal to the minimum distance in which a driver traveling at night and in rainy conditions, can identify a road hazard and stop in time in order to avoid hitting it. This distance is dependent upon the posted traffic speed, and based upon the posted speed of 65 MPH, one SSSD is equal to 645' from the tunnel portal. The following satellite image identifies the locations where the measurements were performed.



The measurement process was begun with the eastbound portal at 5:30 AM. The technicians then moved to the westbound portal and performed that first measurement at 6:00 AM. The process was then repeated, moving back-and-forth between portals, until the last measurement was performed at the westbound portal at 8:00 PM. This entire process resulted in the acquisition of hourly luminance readings for both portals.


Photos of Technicians using ADOT's luminance meter and Fry lens to perform one of the hourly Lseq measurements of the westbound portal at 3rd Street. The meter is positioned at the location described earlier, and aimed at the roadway surface within the portal, but measures the overall quantity of luminance (brightness, in candelas-per-square-meter) that is visible to the average driver's eye at a distance of one SSSD from the portal.

Eastbound Portal

Westbound Portal

Once the hourly Lseq luminance measurements are acquired, these values are utilized in conjunction with the Safety Rating Number (SRN) to calculate the minimum level of L_{TH} illumination that needs to be provided in the Threshold in order to achieve a reasonable level of safety for vehicles entering the tunnel portals. The algorithm is arranged so that the user first needs to input the SRN value that they would like to achieve, and then the algorithm produces the recommended minimum L_{TH} value. As the amount of ambient daylight changes over the course of a day, so do the hourly Lseq measurements and the resulting calculated L_{TH} values. RP-22-11 is based upon a minimum recommended SRN of 4.7, and so that factor has been utilized in producing the recommended minimum L_{TH} values in the following table and graph.

Lseq Measurements Of Both Tunnel Entrances, Performed on Saturday, June 11, 2011

Eastbound		**Westbound**	
Measurement Time of day	*Measured* Lseq Value at Portal (cd/m^2)	Measurement Time of day	*Measured* Lseq Value at Portal (cd/m^2)
5:30 AM	44	6:00 AM	108
6:30 AM	3,308	7:00 AM	241
7:30 AM	2,110	8:00 AM	284
8:30 AM	1,144	9:00 AM	302
9:30 AM	628	10:00 AM	310
10:30 AM	432	11:00 AM	323
11:30 AM	303	12:00 PM	296
12:30 PM	235	1:00 PM	329
1:30 PM	237	2:00 PM	458
2:30 PM	239	3:00 PM	652
3:30 PM	218	4:00 PM	902
4:30 PM	196	5:00 PM	1,384
5:30 PM	162	6:00 PM	1,578
6:30 PM	99	7:00 PM	570
7:30 PM	14	8:00 PM	1

For a final tunnel design, an equivalent veiling luminance (Lseq) analysis should be performed for the tunnel better representing the approaching driver's adaptation level and a therefore providing a more refined Lth value for the tunnel. This analysis would consist of luminance readings of surfaces in the within the drivers field of view at both portals, under various climatic conditions, during various times of the day. It is also possible to estimate variations in brightness conditions through a more limited set of readings and applying daylighting design techniques to determine other conditions.

As part of this study, a limited number of luminance readings were taken at both portals in the morning and afternoon to briefly compare to the IES RP-22-11 table method approach. The readings were taken on June 4, 2011 with clear skies. The results are:

<u>Westbound – 10:30 AM</u>

Sky –	6,300 to 7,400 cd/m^2
Road –	2,500 cd/m^2
Portal Surfaces –	1,900 to 7,000 cd/m^2
Landscaped Areas –	7,100 cd/m^2

<u>Westbound – 4:00 PM</u>

Sky –	10,000 to 14,500 cd/m^2
Road –	11,000 cd/m^2
Portal Surfaces –	770 to 1,000 cd/m^2
Landscaped Areas –	4,000 cd/m^2

<u>Eastbound – 10:45 AM</u>

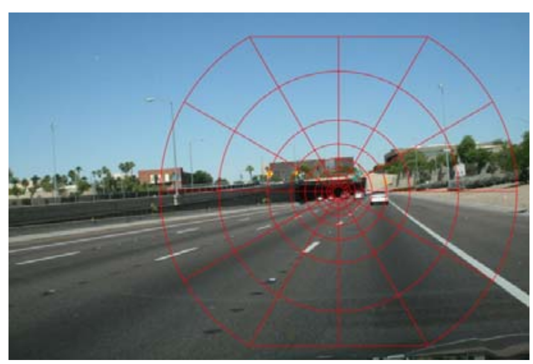
Sky –	6,000 to 9,600 cd/m^2
Road –	5,500 cd/m^2
Portal Surfaces –	900 cd/m^2
Landscaped Areas –	5,200 cd/m^2

<u>Eastbound – 4:15 PM</u>

Sky –	3,400 to 8,200 cd/m^2
Road –	2,100 cd/m^2
Portal Surfaces –	6,000 cd/m^2
Landscaped Areas –	6,000 cd/m^2

Using these measured luminance values, it was then possible to perform a partial Lseq analysis to determine an estimated L_{TH} value based on the condition of highest adaptation luminance.

For I-10 Westbound, the calculated Lseq for the peak case (4:00 PM readings) with this limited data set would suggest a required L_{TH} of 429 cd/m^2 using an SRN of 4.7. An SRN of 4.7 was used in the development of the Table values in RP-22 and is directly comparable.



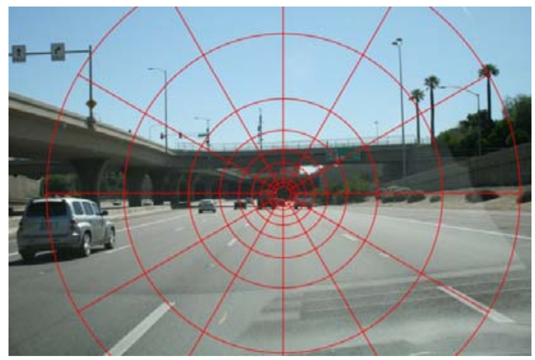
(Table 4)

AVERAGE LUMINANCE OVER EACH RING SECTION/

SECTION	RING NUMBER 1	2	3	4	5	6	7	8	9	SUM
1	0.20	0.50	0.50	0.70	0.70	14.00	14.50	10.00	NC	41.10 kcd/ M2
2	0.20	0.20	0.20	0.50	2.00	14.00	14.50	14.50	10.00	56.10 kcd/ M2
3	0.20	0.20	5.00	0.20	1.00	1.00	2.00	2.00	14.50	26.10 kcd/ M2
4	0.20	0.50	11.00	5.00	11.00	11.00	11.00	11.00	2.00	62.70 kcd/ M2
5	0.20	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	88.20 kcd/ M2
6	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	NC	88.00 kcd/ M2
7	11.00	11.00	11.00	11.00	11.00	11.00	11.00	11.00	NC	88.00 kcd/ M2
8	0.20	0.20	0.20	11.00	1.00	11.00	11.00	11.00	11.00	56.60 kcd/ M2
9	0.20	0.20	0.20	0.40	0.20	1.00	11.00	11.00	11.00	35.20 kcd/ M2
10	0.20	0.30	0.50	0.40	0.50	1.00	2.00	14.50	14.50	33.90 kcd/ M2
11	0.20	0.50	0.50	0.70	0.70	5.00	14.50	14.50	10.00	46.60 kcd/ M2
12	0.20	0.50	0.50	0.70	0.70	14.00	14.50	10.00	NC	41.10 kcd/ M2
									Lij=	663.60 kcd/ M2
										x 5.131E-04
									Lseq=	340.49 cd/ M2

					DESIGN				
SRN=	1	2	3	4	4.7	6	7	8	9
C=	0.719	0.543	0.423	0.342	0.301	0.249	0.223	0.205	0.193
Lth=	104 cd/ M2	152 cd/ M2	223 cd/ M2	328 cd/ M2	**429 cd/ M2**	706 cd/ M2	1,036 cd/ M2	1,521 cd/ M2	2,232 cd/ M2
Lth/ Lseq=	0.30	0.45	0.66	0.96	1.26	2.07	3.04	4.47	6.56

For I-10 Eastbound the calculated Lseq for the peak case (4:00 PM readings) with this limited data set would suggest a required L_{TH} of 300 cd/m^2 using an SRN of 4.7.



(Table 5)

AVERAGE LUMINANCE OVER EACH RING SECTION/

SECTION	RING NUMBER 1	2	3	4	5	6	7	8	9	SUM
1	0.20	0.50	0.90	0.90	9.60	9.60	9.60	8.00	NC	39.30 kcd/ M2
2	0.20	0.20	0.90	0.90	9.60	9.60	7.00	9.60	9.60	47.60 kcd/ M2
3	0.20	0.20	0.90	0.90	0.90	0.90	2.00	2.00	8.00	16.00 kcd/ M2
4	0.20	0.20	0.90	5.00	5.00	5.00	5.00	5.50	5.50	32.30 kcd/ M2
5	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	49.50 kcd/ M2
6	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	NC	44.00 kcd/ M2
7	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	NC	44.00 kcd/ M2
8	0.20	0.20	0.20	5.50	5.50	5.50	5.50	5.50	5.50	33.60 kcd/ M2
9	5.50	5.50	5.50	5.50	5.50	5.50	5.00	5.00	5.00	48.00 kcd/ M2
10	0.90	0.90	0.90	0.90	0.90	0.90	2.00	4.00	6.00	17.40 kcd/ M2
11	0.20	0.90	0.90	0.90	9.60	9.60	9.60	9.60	9.60	50.90 kcd/ M2
12	0.90	0.90	0.90	0.90	9.60	9.60	9.60	9.60	NC	42.00 kcd/ M2
									Lij=	464.60 kcd/ M2
										x 5.131E-04
									Lseq=	238.39 cd/ M2

					DESIGN				
SRN=	1	2	3	4	4.7	6	7	8	9
C=	0.719	0.543	0.423	0.342	0.301	0.249	0.223	0.205	0.193
Lth=	73 cd/ M2	106 cd/ M2	156 cd/ M2	229 cd/ M2	**300 cd/ M2**	494 cd/ M2	725 cd/ M2	1,065 cd/ M2	1,563 cd/ M2
Lth/ Lseq=	0.30	0.45	0.66	0.96	1.26	2.07	3.04	4.47	6.56

Based upon these Lseq evaluations, an L_{TH} of 350 cd/m^2 is a reasonable value for comparing lighting alternatives for this tunnel. Final design should include additional light level readings and Lseq analysis to refine the proper design value.

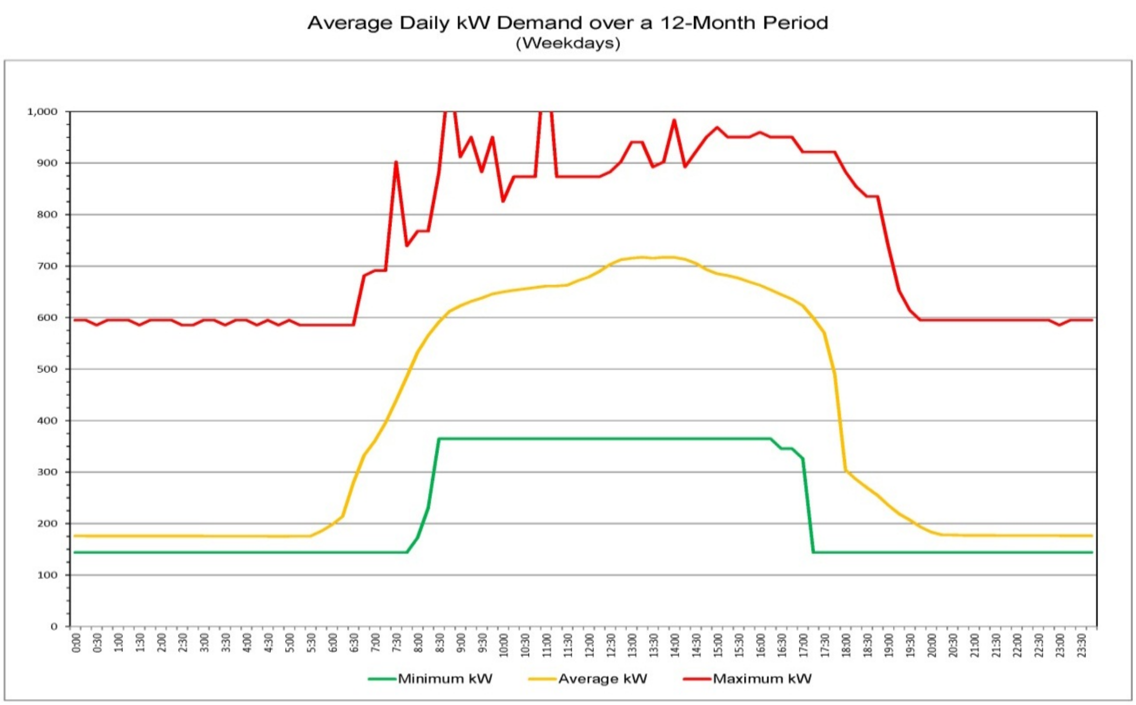
The original lighting design was apparently based upon a combination of the IESNA document RP-22-87 and the equivalent CIE document, and lists a calculated Threshold luminance (L_{TH}) level of 287 cd/m^2. However, the calculated simulation/analysis for the existing lighting system, designated as "Existing Base Case", identifies an existing

L_{TH} of only 110 cd/m^2. These calculated values have subsequently been verified via representative field measurements.

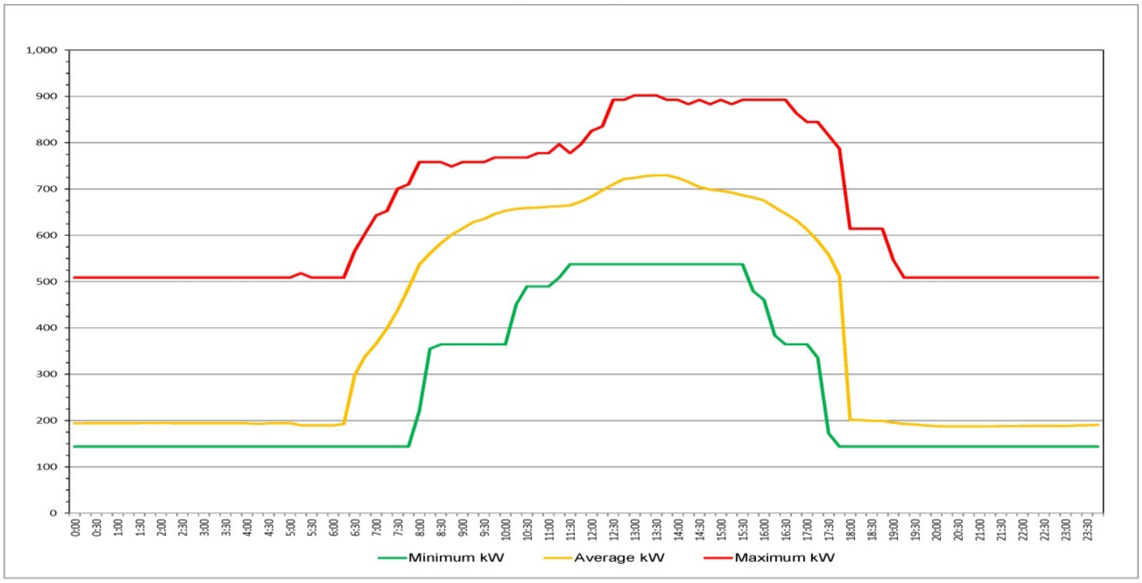
The Lseq analysis discussed earlier is based upon modern design practices, and cannot be accurately applied toward aspects of the original design. Modern design practices utilize zone lengths that are different from those utilized in 1987, and even includes a zone known as "Threshold Zone - 2nd Half" that wasn't even established until earlier this year. Therefore, in order to compare the suggested L_{TH} values against the existing luminance levels, it is necessary to first re-evaluate the existing lighting as if it were designed under the current RP-22 document, and with the current zone lengths and types. This re-evaluation and analysis, designated as the "Revised Base Case", results in an increase of the current L_{TH} value to 158 cd/m^2 – which is valid to compare against the Lseq suggested values of 300 – 429 cd/m^2.

Not only is the lighting system operating at a level that is less than 50% of both the original design goal and modern design practices, but it seems to have been doing so for at least the last 12 months, and may simply not be capable of recovering most of what has been lost. The following charts graph the average weekday and weekend kW demand (electric load) required by the tunnel over a 24-hour period. The charts are based upon load data obtained directly from APS, and include kW values for every 15-minute period over the last 12 months. The load profile shows a flat pattern over most of the day, which indicates that the eastbound lighting is quickly ramping-up to full output in the morning (as expected), but is then remains operating at full output until the afternoon, at which time the westbound lighting starts to ramp-up to full.

This pattern is quite different from the expected load pattern, which should experience one peak in the morning, another peak in the late afternoon, and with a "valley" during the middle of the day when the lighting in both tunnels/tubes should be operating at reduced levels (since the is overhead and not directly in drivers' eyes.



Average Daily kW Demand for a 12-Month Period
(Weekends)



b. Original Design Conditions

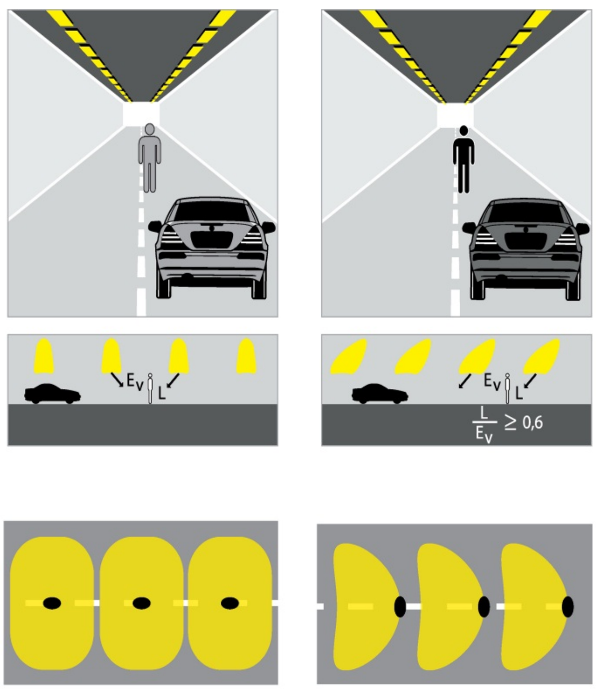
The luminaires in the Deck Park Tunnel have all been in place for more than 20 years. Because of the environmental conditions that are normal for a tunnel (vibration, heat, dust/dirt, acidic vehicle exhaust, etc.), tunnels are a very harsh environment for any type of electrical hardware. This is evidenced by the current condition of the luminaire lenses & reflectors, as well as the degraded condition of the electrical channel into which the luminaires are plugged. Based upon a visual inspection of the luminaires, as well as industry standard practices, it is estimated that the luminaires will all need to be replaced within 5 years, and this replacement will provide an excellent opportunity for implementing energy-efficient upgrades of both the luminaires and lighting controls.

Existing Tunnel Luminaires			
Luminaire Type	**Luminaire Wattage (including ballast)**	**Eastbound Quantity**	**Westbound Quantity**
70-watt HPS, symmetric	87	452	457
70-watt HPS, counterbeam	87	145	144
150-watt HPS, symmetric	183	74	74
250-watt HPS, symmetric	305	152	151
250-watt HPS, counterbeam	305	317	320
400-watt HPS, counterbeam	468	460	508
Luminaires Per Tube		1,600	1,654
Total Luminaires		**3,254**	
Wattage Per Tube		423,806	447,228
Total Wattage		**871,034**	

The existing lighting system is composed of General Electric Tunnel-Guard luminaires with high-pressure sodium (HPS) light sources and magnetic ballasts. *(See Attachment #2)*

The luminaires range in wattage from 70 watts to 400 watts, and possess two different photometric distributions – Symmetric, and a type of asymmetric distribution known as Counterbeam. Symmetric distribution provides fairly uniform illumination in all directions around the luminaire, helps to illuminate the upper portion of the tunnel walls as well as the road surface, and is utilized throughout the length of the tunnel. Counterbeam distribution projects a majority of the illumination onto the road surface and the lower portion of the tunnel walls, and in a direction counter to the direction of vehicle travel. Counterbeam distribution is utilized to provide the higher levels of light that are required in the Threshold and Transition Zones.

SYMMETRICAL LIGHTING **COUNTERBEAM LIGHTING**



OVERHEAD VIEW OF LIGHTING DISTRIBUTION PATTERNS

The intensity and directionality of Counterbeam lighting provides benefits beyond just the amount of illumination of the walls and roadway, but also illuminates objects from the rear and creates a situation of "negative contrast" that further aides in the identification of potential roadway hazards. Notice in the adjacent graphic that the pedestrian is actually more easily identifiable to the driver under Counterbeam lighting, even though a majority of the illumination is from behind. Therefore, even though the existing lighting layout is more than 20 years old, this combination of Symmetric and Counterbeam luminaires is still considered to be one of the most energy-efficient strategies by which to illuminate this particular tunnel application, and should be incorporated in future redesigns of the lighting.

c. Base Cases

Existing Base Case

In order to measure the potential reductions in operating costs that can be expected as a result of implementing the recommended Options, it is necessary to first have a starting-point against which all of the recommended Options can be compared. This operating scenario is henceforth designated as the "Existing Base Case", and is based upon the: existing luminaires, luminaire locations, mounting heights, lighting controls, operating schedule, surface colors & reflectances, maintenance schedule & costs, etc. This data has been utilized to create a detailed photometric model of this operating scenario, of which 24"x36" hard-copies have been generated, and are located in the Appendices of this report. The following table summarizes the photometric performance of the Existing Base Case, as well as a life-cycle-cost (LCC) analysis. A LCC analysis requires the inclusion of the initial project cost, and so a value of $2,000,000 has been estimated for the original installed cost of the existing lighting.

Existing Base Case			
		Day	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	110	1.4
Threshold Zone 2nd Half	luminance level	n/a	
Transition Zone 1	luminance level	26	1.5
Transition Zone 2	luminance level	7.9	2.7
Transition Zone 3	luminance level	7.4	2.4
Interior Zone	luminance level	6.9	2.1
Implementation Cost (Estimated portion of the original construction cost that went toward the purchase and installation of the original luminaires. Costs for the original electrical infrastructure are NOT included.)		$2,000,000	
Yearly Energy Cost		$335,219	
Yearly Maintenance Cost		$45,000	
Yearly Savings		n/a	
Simple Payback Years		n/a	
25-Year Life-Cycle-Cost Present Value		$5,999,310	

Revised Base Case

The tunnel was designed in conformance with the 1987 version of the IESNA document "Recommended Practice for Tunnel Lighting", or RP-22. There have been two revisions of that document since then, and the most recent version changes the lengths of the various Zones, and introduces a new Zone that consists of the second half of the original Threshold Zone and allows for a reduction of the luminance level within this new Zone. These revisions create a challenge when it comes to comparing potential energy-efficient Options (the evaluations thereof should be based upon the current version of RP-22) against the Existing Base Case (which is based upon the 1987 version of RP-22). It was therefore determined, that in order to perform valid comparisons, it would first be necessary to take the existing tunnel data, and re-evaluate all of it based upon the revised parameters in the 2011 version of RP-22. This operating scenario will henceforth be referred to as the "Revised Base Case". This re-evaluated data was again utilized to create a detailed photometric model, of which 24"x36" hard-copies have been generated, and are located in the Appendices of this report.

Revised Base Case			
		Day	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	158	1.5
Threshold Zone 2nd Half	luminance level	119	1.6
Transition Zone 1	luminance level	43	1.6
Transition Zone 2	luminance level	8.8	2.7
Transition Zone 3	luminance level	7.6	2.4
Interior Zone	luminance level	7.5	2.1
Implementation Cost (for the direct replacement of the existing HPS luminaires, recycling of the removed luminaires, and application of a white coating to vertical bulkheads in Thresholds and concrete curbs throughout the length of the Tunnel)		$3,500,000	
Yearly Energy Cost		$335,219	
Yearly Maintenance Cost (includes additional cleaning costs for including the white coating in the periodic Tunnel cleanings)		$49,000	
Yearly Savings		n/a	
Simple Payback Years		n/a	
25-Year Life-Cycle-Cost Present Value		$9,610,246	

The preceding table summarizes the photometric performance of the Revised Base Case, as well as a life-cycle-cost (LCC) analysis. As mentioned earlier in the report, it is estimated that all of the luminaires will need to be replaced within the next 5 years. Therefore, since this is a cost that will have to be expended independent of this study, the LCC analysis includes this estimated Implementation Cost, which is based upon the installed cost for replacing all of the existing high-pressure sodium (HPS) luminaires with newer versions of the same luminaires, on a one-for-one basis.

The Implementation Cost also includes a $50,000 upgrade that should be performed even though the current state-of-the-science has difficulty with quantifying the exact impact upon the luminance levels or functionality of the tunnel. The tunnel walls include a natural, exposed concrete "curb" that is about 30" tall, and runs the length of both tunnels/tubes. This "curb" should be painted with a specialized white coating that possesses a reflectance of 88%. Coating the inside of the tunnel of the tunnel provides a contribution to both the overall luminance of the tunnel and the visibility of objects in the tunnel itself. Both of these contributions are due to the improved reflectivity of the wall surfaces.

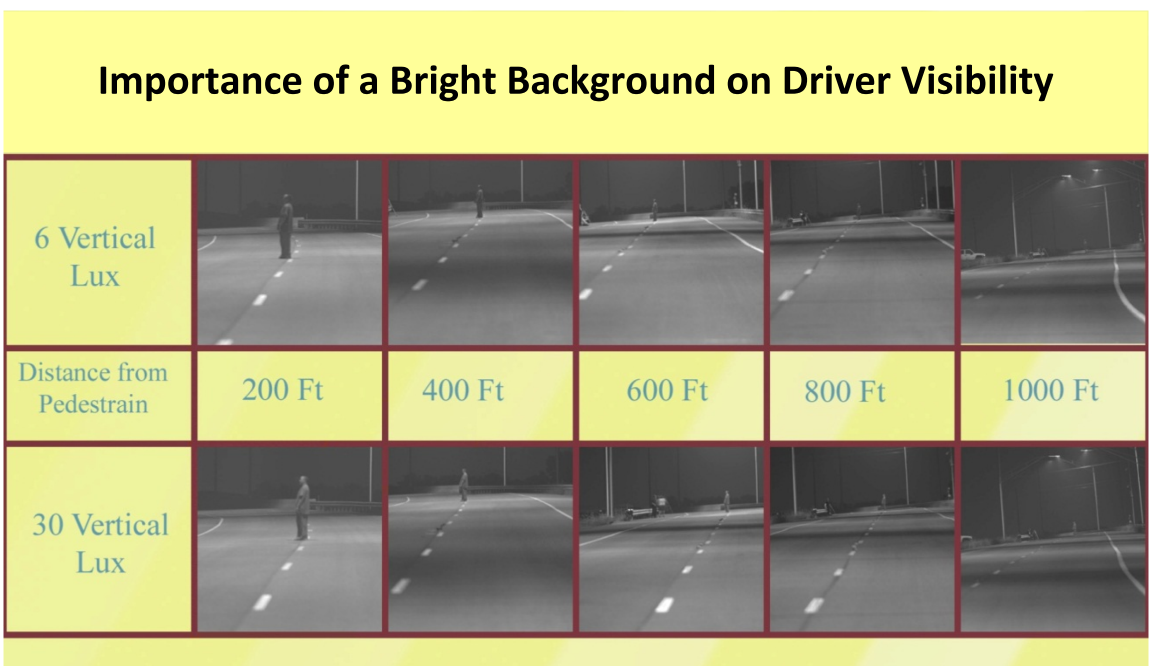
Visibility is based on contrast. In order for a driver to detect an object in the roadway, it must have contrast to the background, meaning that it appears differently than the background. In order to make an object visible, a lighting design must provide a contrast level that is greater than the objects threshold contrast. This threshold is the contrast level where an object just transitions from invisible to visible. Every object has a threshold contrast that is based on the size of the object, the adaptation luminance level of the driver, the age of the driver, and the observation time. In a roadway situation, neither the age of the driver, nor the observation time or size of the object can be controlled. Therefore, what must be controlled via the lighting design are the adaptation luminance of the driver's eye, how much light strikes the object, and the luminance of the background behind the object to be seen.

The strategies that can be employed to control the adaptation luminance are to make the threshold contrast as low as possible, and then provide a lighting design that allows objects to appear in the tunnel with as much contrast as possible. The higher an objects actual contrast is above the threshold contrast, the more likely drivers are to see it.

Controlling the adaptation luminance is achieved by controlling the field of view of the driver. This is the purpose of the L_{seq} analysis. By controlling the adaptation of the driver's eye, and providing adequate luminance in the tunnel entrance, the lighting design strives to maximize the visibility by minimizing the threshold contrast. Making the walls and the ceiling of the tunnel bright will provide a higher luminance level in the tunnel, and reduce the amount of light required due to inter-reflections of the light from the wall and ceiling of the tunnel. In the Deck Park Tunnel, there is a curved wall that provides an additional benefit. As this curved wall is visible on the approach, providing a brighter wall will further reduce the black hole effect.

The other aspect, providing high contrast levels on the objects that may appear in the tunnel, is achieved in two ways: controlling the background behind the object, and controlling the vertical illuminance on the face of the object. As part of the existing Counterbeam lighting system, the light is directed towards the driver, and very little lands on the face of any objects in the roadway, resulting in the objects appearing in a dark silhouette against the background. Providing as bright a background as possible will ensure that any object will appear in the desired dark silhouette. This impact is further enhanced by the curved wall that is visible from the tunnel entrance, as most objects will appear more readily against the bright wall.

As a result, the painting of the wall with a high reflectance material provides two additional benefits. The first is the higher adaptation luminance in the tunnel entrance, and the second is better control of the visibility of objects and vehicles in the tunnel due to control of the background on which objects appear. If possible, it is recommended that the entire curved wall be painted. However, given possible limitations of the materials, painting the "curb" area only will still provide a benefit, primarily in the assessment of object visibility. It should be noted, however, that maintenance of the coating is a critical factor. Cleaning of the painted surface must be performed at regular intervals to maintain performance of the reflective material. *(See Attachment #3)*



Vertical “Bulkheads” inside the eastbound threshold that should be treated with a high-reflectance white coating

Test Area inside the eastbound threshold where the white coating has been applied to the 30” high concrete “curb”

d. Option 1 – Increase the Luminance Level in the Threshold (L_{TH}) via the Replacement of the Existing HPS Luminaires with New, Higher-Wattage, HPS Luminaires.

It was requested that this study should include an analysis of how operating costs for the tunnel lighting would be affected if the average Luminance level in the Threshold Zone were to be increased from the existing level, to either 250 cd/m^2 or 350 cd/m^2.

Since the existing luminaires will soon have to be replaced anyway, the simplest method for achieving this increase in Luminance (although far from the most energy-efficient method), would be to select higher-wattage HPS luminaires, such as 1,000-watt and 400-watt, instead of simply replacing the existing 400-watt and 250-watt luminaires. The following table summarizes the photometric performance of these Options, as well as a life-cycle-cost (LCC) analysis. The LCC analysis includes the costs to purchase and install the new luminaires, the increased energy costs, and the increased maintenance costs due to larger lamps and ballasts.

Option 1 – Increase Threshold Luminance via Higher-Wattage HPS Luminaires

		250 cd/m^2		**350 cd/m^2**	
		Day	**Night**	**Day**	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	250	2.5	350	2.5
Threshold Zone 2nd Half	luminance level	175	2.5	245	2.5
Transition Zone 1	luminance level	69	2.5	96	2.5
Transition Zone 2	luminance level	28	2.5	39	2.5
Transition Zone 3	luminance level	17	2.5	24	2.5
Interior Zone	luminance level	11	2.5	11	2.5
Implementation Cost (Incremental cost, between the cost of the required upcoming replacement of the existing luminaires and the cost for specifying higher-wattage HPS luminaires on a one-for-one basis., as well as the associated cost for upgrading the distribution panels.)		$100,000		$1,500,000	
Yearly Energy Cost		$552,743		$754,410	
Yearly Maintenance Cost (includes additional cleaning costs for white coating)		$51,500		$54,000	
Yearly Savings		n/a		n/a	
Simple Payback Years		n/a		n/a	
25-Year Life-Cycle-Cost Present Value		$12,991,265		$17,402,086	

As was previously discussed, in order to add this much lighting load, it will be necessary to upgrade portions of the tunnel's electrical infrastructure. In order to achieve an L_{TH} of 250 cd/m^2 (2.3 times the existing level), this upgrading will involve adding capacity to the electrical panels located in the four Vent Rooms. In order to achieve an L_{TH} of 350 cd/m^2 (3.2 times the existing level), this upgrading will involve a substantial upgrade to all of the tunnel's electrical infrastructure, including the utility transformers, in order to support the substantial increase in load.

e. Option 2 – Apply Darker Finishes to the Surfaces Near the Tunnel Entrances

The Lseq analysis that calculates the suggested minimum L_{TH} value for a tunnel threshold evaluates all of the stray light that impacts a driver's eye (or in this case the lens of the luminance meter), which includes direct input from the bright sky and reflected input from surrounding materials. High luminance levels from these direct and indirect (reflected) sources results in excessive luminance contrast ratios, which makes it more difficult for the driver to see beyond the tunnel entrance and into the Threshold Zone. As a result, the suggested minimum L_{TH}, and associated luminaire wattage, must be increased in order to compensate for this high ambient luminance.

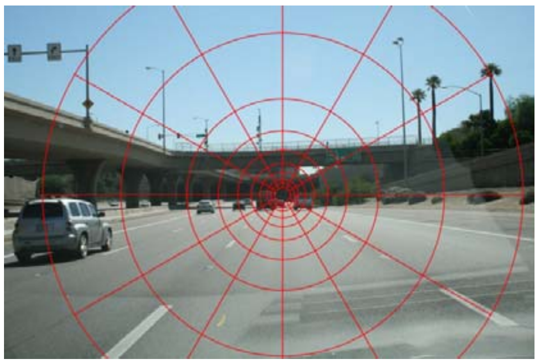
Reducing the direct luminance from the sun or bright sky can only be accomplished by adding a physical barrier, such as the large signage structures that were proposed during the August 30th presentation. Reducing the reflected luminance can be accomplished by replacing the light-colored finishes with darker colors that reflect less luminance. Therefore, it is recommended that a dark-colored stain or paint be applied to all vertical surfaces near the tunnel entrances. The landscape materials should either be painted a darker color, or covered with a layer of darker material.

Option 2 – Apply Darker Finishes to the Surfaces Near the Tunnel Entrances			
		Day	**Night**
Threshold Zone 1st Half (Only this Zone will be "affected" by the upgrade.)	luminance level (cd/m^2)	*168* (equivalent)	1.5
Threshold Zone 2nd Half	luminance level	119	1.6
Transition Zone 1	luminance level	43	1.6
Transition Zone 2	luminance level	8.8	2.7
Transition Zone 3	luminance level	7.5	2.4
Interior Zone	luminance level	7.5	2.1
Implementation Cost (For applying darker finishes to the vertical surfaces, and applying a layer of darker gravel on top of the existing landscape material.)		$750,000	
Yearly Energy Cost		$335,219	
Yearly Maintenance Cost (includes additional cleaning costs for white coating)		$49,000	
Yearly Savings		n/a	
Simple Payback Years		n/a	
25-Year Life-Cycle-Cost Present Value		$9,677,427	

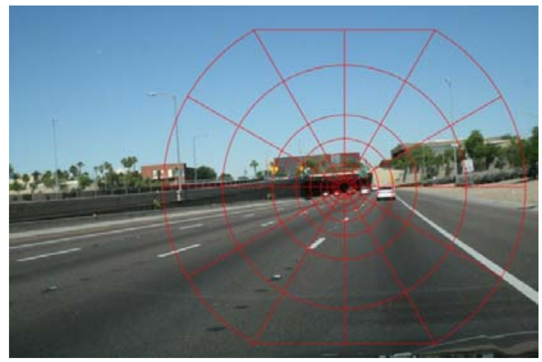
ADOT has suggested, for the purpose of this analysis, that Frazee No. 5264D known as "Chestnut" be assumed for use as the darker stain or paint, and that a darker color of granite known as "Saddleback Brown" be assumed for the landscaping. The local manufacturer representatives for these products have been unable to provide any technical specifications as to the reflectivity characteristics, and so a reduction in reflectivity of 50% has been assumed for the purpose of this analysis.

Reducing the reflectance value of the vertical surfaces and landscaping material by 50% will reduce the suggested L_{TH} in the Thresholds by about 10 cd/m^2, and darker/less-reflective colors will reduce the suggested L_{TH} even more. This reduction in L_{TH} can serve either to improve driver visibility when entering the Thresholds, or allow for a corresponding reduction in luminaire wattage & energy consumption within the Threshold Zones.

This analysis utilized the same type of "ring graphs" as was discussed earlier, in the section on the Lseq analysis.



Eastbound Portal



Westbound Portal

f. Option 3 – Construct Exterior Shade Structures Adjacent to Tunnel Entrances

As was previously discussed; the most energy-efficient method for achieving an increased L_{TH} of 250 cd/m^2, and the only method for achieving an increased L_{TH} of 350 cd/m^2 without having to upgrade the electrical infrastructure throughout the tunnel, would be to construct a Shade Structure adjacent to each tunnel entrance. This Option will allow ADOT to substantially increase the luminance level in the Threshold Zones, while maintaining about the same costs for energy and electrical maintenance.

The proposed Structures would span the width of the eastbound and westbound lanes at the tunnel entrances, and will extend outward from the entrances approximately 325’. The Shade Structure functions by “relocating” the approximately 325’-long “1st Half of the Threshold Zone” (which is the only portion of the Zone that requires the full 250 or 350 cd/m^2), to outside of the tunnel and underneath the Shade Structure, where all of the daytime illumination needs would be met by natural daylight. The nighttime illumination needs would be provided by LED luminaires. The remaining portion of “Threshold” in the tunnel will be re-designated as the “2nd Half of the Threshold Zone” (as per RP-22-11), which only needs to be illuminated to an average of 70% of the target L_{TH} level, and this is achievable without upgrading any of the electrical infrastructure.

Option 3 – Construct Exterior Shade Structures Adjacent to Tunnel Entrances			
		Day	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	350	2.5
Threshold Zone 2nd Half	luminance level	245	2.5
Transition Zone 1	luminance level	96	2.5
Transition Zone 2	luminance level	39	2.5
Transition Zone 3	luminance level	24	2.5
Interior Zone	luminance level	11	2.5
Implementation Cost (For constructing the two Shade Structures as per the concepts detailed in this section of the report.)		$8,000,000	
Yearly Energy Cost		$335,219	
Yearly Maintenance Cost (includes additional costs for including the Shade Structures in the periodic cleaning of the Tunnel.)		$54,000	
Yearly Savings		$0	
Simple Payback Years		n/a	
25-Year Life-Cycle-Cost Present Value		$17,719,972	

The following 12 pages comprise a special section that presents detailed conceptual information on the proposed Shade Structures. This section was prepared by:

Michael D. Kroelinger, Ph.D., AIA, FIIDA, LC
Principal, MK Design Associates

The following contains a *conceptual* strategy for potential Shade Structures that could be constructed at both tunnel entrances. The potential Structures are proposed to accomplish several goals, including: reduction of cd/m^2 at the tunnel entrance, reduction of energy consumption within the first zone of the tunnel, improved visibility, and reduction of sun and sky brightness during morning or afternoon hours (depending on direction of travel). This strategy is conceptual in nature and does not include any design development.

Underlying Assumptions

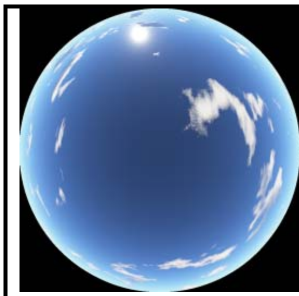
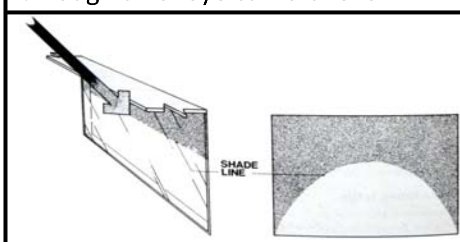
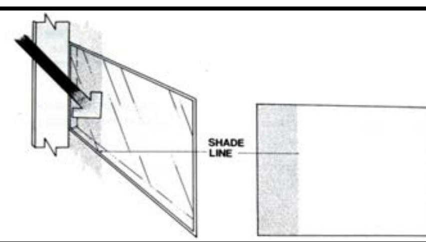
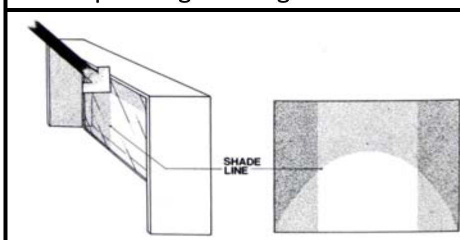
The following underlying assumptions define the shading option to be considered for both the westbound and eastbound tunnel entrances to the deck park tunnel:

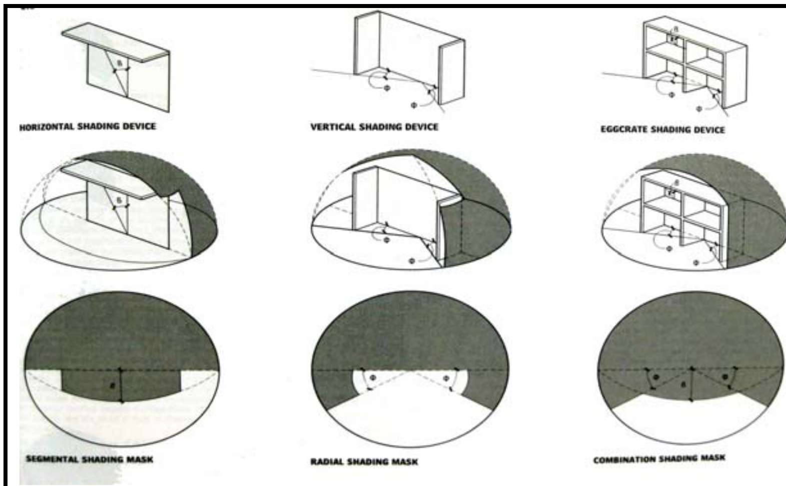
- Critical openings to the east and west.
- Morning or afternoon low sun angles are a problem depending on direction of travel and time of day.
- Sun position varies according to time of the day and the year.
- Skydome brightness going into *and* coming out of the tunnel is also a problem.
- Reduction of cd/m^2 both under a long, horizontal east (or west) shading structure and in threshold area of tunnel portal is *critical* for visibility and energy conservation.
- A horizontal shading concept is the *only* viable option in spite of east-west facing direction.
- The shading structure likely will perform better, especially for high sun angles (e.g. summer) if it is slightly slopped downward toward the north and has great length.
- Visible transmittance of the shade structure will need to be well below 30% to meet cd/m^2 requirements.
- The *length* of the east (or west) facing horizontal element is critical for reducing sky brightness and limiting direct sun penetration.
- Must define options for structural system and boundary limitations required by ADOT for complete design development and further analysis of the selected option discussed in this report. For example – a lightweight truss frame system with tension cables spaced on 10' O.C. is the desired structural system. Span distances must be analyzed in detail before a system recommendation for the structure can be finalized, and is outside the purview of this report.

Sun Position and Shading Overview

Key information that impacts the shading design is summarized and illustrated below. This background information was reviewed by the project team during the meeting with ADOT staff on August 30, 2011.

- A tunnel entrance, or opening into a building, will be in shade when the sun travels across the obstructed part of the sky (typically called the "skydome").
- Sky obstructions and shading devices can be graphically plotted to construct a shading mask.
- We can accurately determine the times the direct sunlight is blocked from reaching the opening.
- Different compass directions call for *different* shading strategies for openings.
  - Horizontal overhang – shading mask is a curved shadow line running from one edge of the mask to the other. Best for south-facing openings.
  - Vertical fin – the shading mask creates a vertical shading line. Best for east & west openings.
  - Combination horizontal overhang/vertical fin - the shading mask is combination of both curved and vertical shading lines. Can be used, depending on design, on all compass directions.

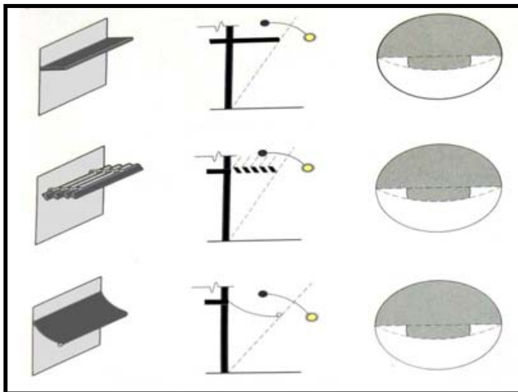
	
View of a clear sky "skydome" as observed through a fisheye camera lens.	Sun path in unobstructed part of the sky.
	
Horizontal shading strategy with corresponding shading mask.	Vertical shading strategy with corresponding shading mask.
	
Combination shading strategy with corresponding shading mask.	



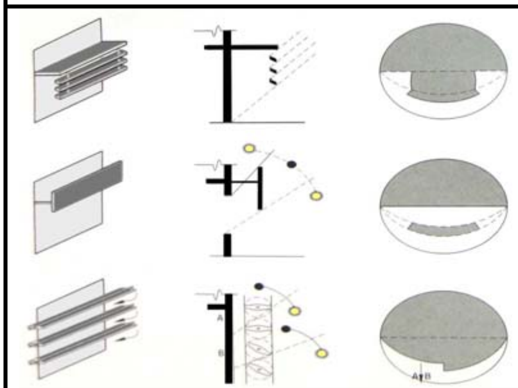
Basic shading devices with their obstruction effect on the skydome with their projected shading masks (The American Institute of Architects (2010), Architectural graphic standards for Residential Construction, Shading Masks and Shading devices, John Wiley & Sons).

Additional information about these key strategies is illustrated below and includes (The American Institute of Architects (2010), Architectural graphic standards for Residential Construction, Shading Masks and Shading devices, John Wiley & Sons):

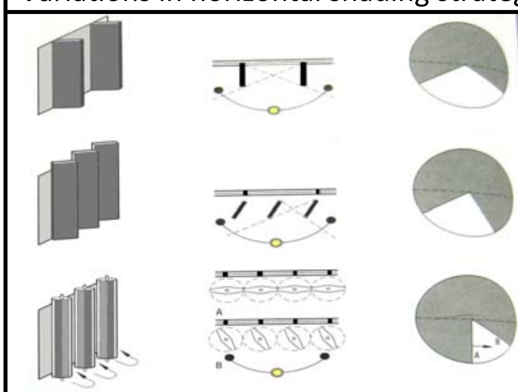
- Horizontal overhangs are the most efficient toward or around southern orientations, their mask characteristics are segmental.
- Louvers parallel to the wall have the advantage of permitting air circulation near the elevation.
- Slanted louvers will have the same characteristics as the solid overhangs and can be made retractable.
- When protection is needed for low sun angles, louvers hung from solid horizontal overhangs are efficient.
- A solid or perforated screen strip, parallel to the wall, cuts out the lower rays of the sun.
- Moveable horizontal louvers change their segmental mask characteristics according to their positioning.
- Vertical fins serve well toward the east and west orientations. Their mask characteristics are radial.
- Vertical fins oblique to the wall result in an asymmetrical mask. Separation from the wall prevents heat transmission.
- Movable fins shade the whole wall or expose different directions, according to the sun's position.
- Solid eggcrate with slating vertical fins result in an asymmetrical mask.
- Eggcrate device with movable horizontal elements shows flexible mask characteristics. Because of their high shading ratio eggcrates are efficient in hot climates.



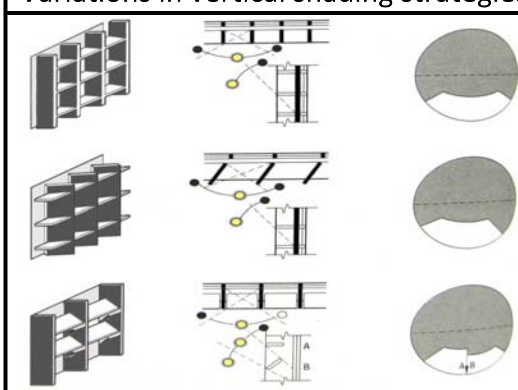
Variations in horizontal shading strategies and their respective shading masks.



Variations in horizontal shading strategies and their respective shading masks.



Variations in vertical shading strategies and their respective shading masks.

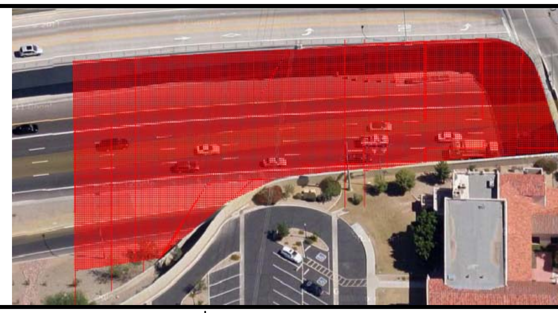


Variations in combination shading strategies and their respective shading masks.

General Design Concept

The general concept discussed in this report is based on a *horizontal shading strategy* using a metal mesh fabric system spanning an approximate area of 40,000 square feet at each tunnel entrance, as illustrated below:

Westbound portal at 3rd Street.



Eastbound at 3rd Avenue

In concept, using the westbound entrance at 3rd Street, the shading structure could be visualized as illustrated below. *The actual design may significantly vary to achieve the required shading results and the actual structural design.*

3-D Sketch view at westbound portal at 3rd Street.

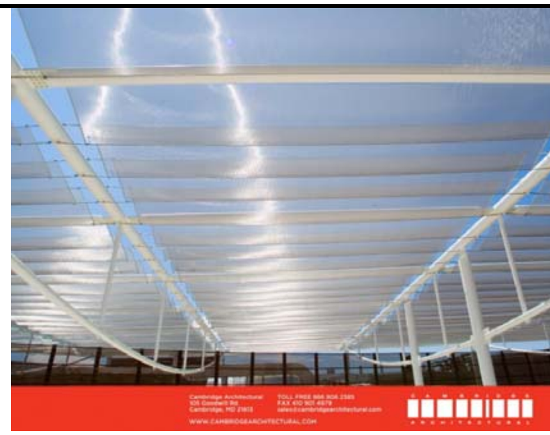
This system has the following characteristics and is based on the "Shade" pattern product by Cambridge Architectural (http://www.cambridgearchitectural.com/):

- A lightweight wire mesh "metal fabric".
- Can be combined with a variety of light-weight structural systems.
- Predictable light transmittance.
- Durability.
- The material is stainless steel.
- Open Area of the standard product is 43% but can be manufactured to produce a lower percentage The deck park project will require an approximate 30% openness factor to achieve the required maximum roadway luminance.
- Material weight is 0.94 lbs./sq. ft @ a 43% openness factor.
- Maximum width: 240"

- Available in custom design lengths for the spans we need.
- Shading system cost estimated at approximately $50.00 per square foot including the proposed tension cable system plus an estimated $32.00 to $40.00 per square foot for a long span light-weight structural system required to support the proposed span across the lanes of the tunnel entrance. Additional roadway lighting within the shading structure will be an estimated $5.00 per square foot.
- Design appearance and shading performance are important and must be assessed in detail during future design development.
- If readers of this report are interested, the manufacturer provides an on-line one hour continuing education program on shading and daylighting with mesh materials (http://www.thecontinuingarchitect.com/course.asp?id=1).

An excellent example of this system with similar needs for a wide/long light-weight structural system for span and for its somewhat similar needs for shade and sun control is the University of Arizona Medical Research Building & Thomas Keating Bioresearch Building located in Tucson. The project, which was designed by the Zimmer Gunsul Frasca Partnership, Los Angeles office, is a canopy-style Ramada shading structure interconnecting two buildings. It was completed in the summer of 2006. The project is illustrated below (photos complements of Cambridge Architectural):

Overall view of University of Arizona “canopy”.



Parallel rows of 4’x43’ panels mounted within a light-weight structural system.

Panel layout using a standard grid.

Each panel is suspended by a tension cable system mounted to the structural system.

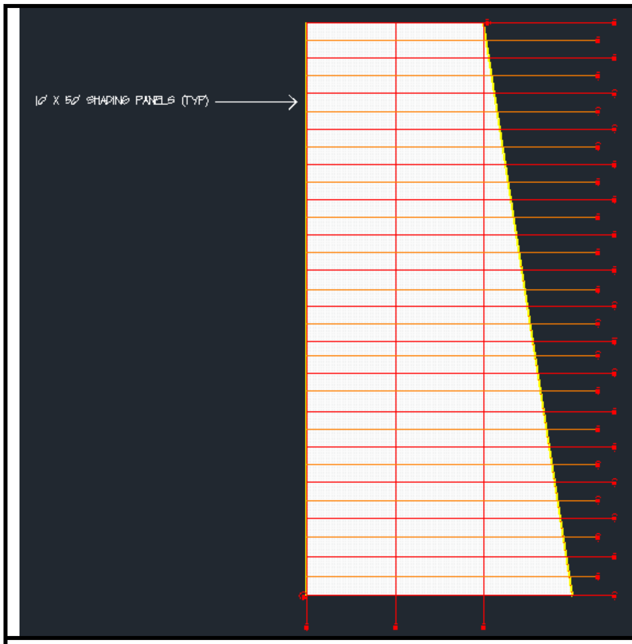
This University of Arizona project system differs from the proposed concept for the Deck Park Tunnel in the following ways:

- Span is less in both compass directions.
- Individual shading panels are smaller in area and in mounting angle (slopped versus a need to overlap panels for complete direct sun control in the deck park concept).
- Structural system for the deck park concept must be based on economical and safe strategies for longer spans and less height for individual trusses.
- Need for the deck park system to be slopped at a to-be-determined angle toward the north for optimal shading during high sun angles.

The systems may be similar in the following ways:

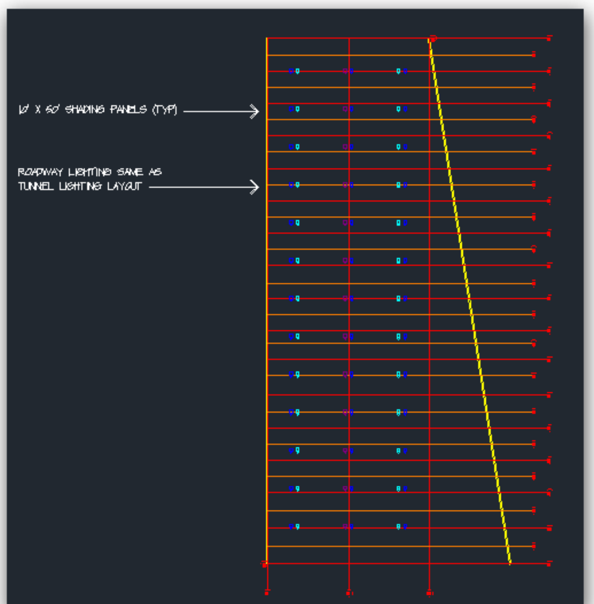
- Use of the “shade” mesh pattern and material.
- A grid pattern of panels mounted using a tensile cable system.
- Same mounting hardware for the cable system; universally used by Cambridge Architectural.
- Achieve shading a large area at entrances (buildings in the case of the Tucson project; tunnel entrance for the deck park project).

The proposed system is based on an estimated area of approximately 40,000 square feet and is represented in the conceptual panel diagram below (based on a width at the tunnel entrance of 100 feet and increasing in width to 150 feet; length is estimated at 324 feet or ½ of the required stopping distance defined by ADOT). The actual design will vary based on accurate site measurements and drawings; this concept is based off Google images of the westbound entrance. The panel layout is based on a nominal 10’x50’ panel length for “typical” panels. Actual panel sizes will be based on later design development work by others. The manufacturer (Cambridge Architectural) will need to determine deflection of the panels for this proposed size; if too much deflection is predicted, panel widths and length will need to change. For example, use of a 5’x50’, or lesser dimension, panel as a second option. The system will also require an extension of the tunnel lighting system, using the same lane layout, as part of the shading structure. The extension of this system is illustrated below using the conceptual plan for the shading system.



Panel layout based on approximate area noted in text above. Layout uses a 10’x50’ typical panel size.

“Shade” product from Cambridge Architectural.



Roadway lighting layout using existing tunnel lighting layout and spacing.

The structural system, which must be defined during design development, will likely need to be based on the following assumptions (per Google photos of the westbound 3rd Street entrance; similar for eastbound 3rd Avenue entrance):

Structural system could be mounted on the 3rd Street off ramp if determined feasible and structurally safe.

Structural system could be mounted above the tunnel entrance as a continuation on 3rd Street.

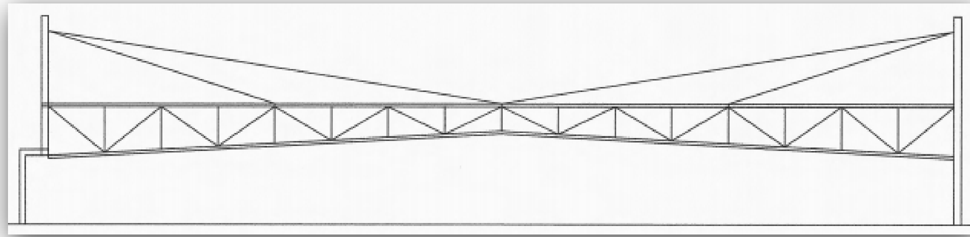
North side structure would likely need to be located to the north of the lower retaining wall for safety; a structural wall or column system would be required. As a separate issue, nighttime lighting will be required due to the shading structure length.

The general concept issues for a light-weight long span structural system was reviewed by Greg Brickey, BDA Engineers. Brickey suggested three possible systems. His email recommendation is as follows:

"I analyzed the trusses a few different ways. I am using *steel pipe* as the structural material in each of the iterations. The choices are:

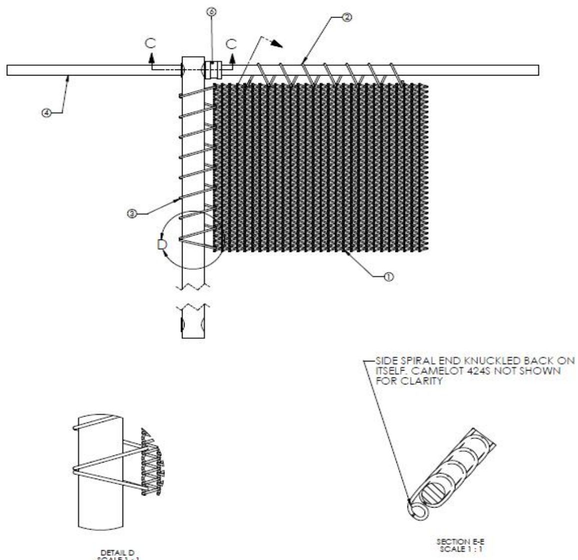
1. A basic flat truss that would be 8 to 10 feet deep and can clear span from the roadway structure to columns located off the roadway right of way. This system is the most simple, and low on wow factor, but it is cost effective and gets the job done.
2. I looked at more of a bowstring configuration; go from 24" at the ends to 10' at the mid-span. These would be more interesting, but more expensive.
3. I also looked at a cable support truss arrangement where the trusses could be much shallower and be supported at mid span with tension cables from columns at both ends. This would be visually interesting, and it would make a statement.

After looking at the analysis, it looks like the cost is going to be in the range of $32 to $40 per square foot. The uncertainty lies with some assumptions regarding the capacity of the existing roadway structure and the ability to sink some deep foundations for the new columns." (J. Greg Brickey, SE, AIA; BDA engineers, ltd.; Scottsdale – Arizona; www.bdaengineers.com; 480.467.7797 v; 480.219.6493 f).

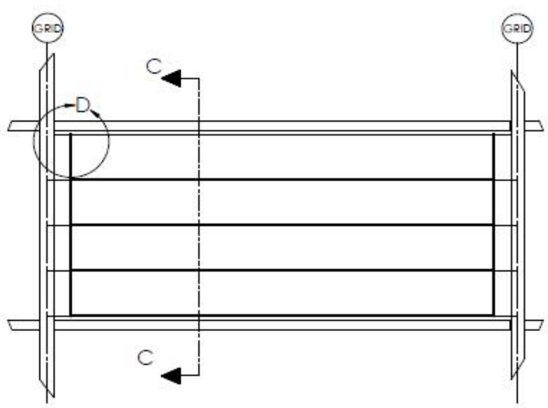


Section sketch for 0ption 3 using a cable truss arrangement, as defined by BDA Engineers.

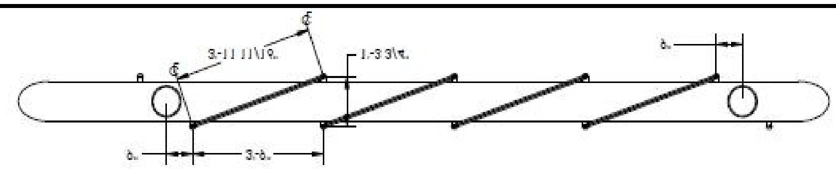
The proposed shading panel system is graphically represented in the following typical details provided by the shading material manufacturer. Actual sizing and design, as noted above, will vary except for the tension cable mounting system which is a standard system used by the manufacturer.



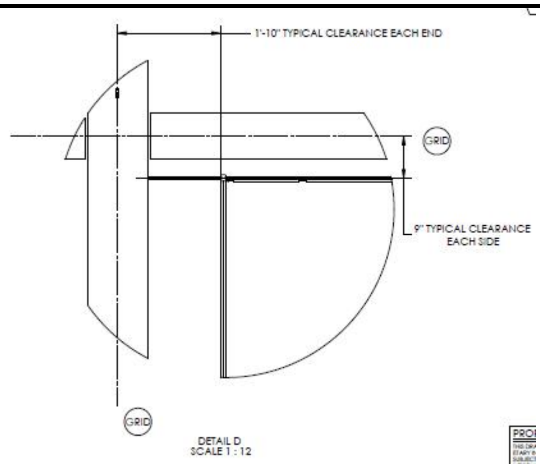
Mounting detail of mesh fabric, pattern shade, to a light-weight structural system.



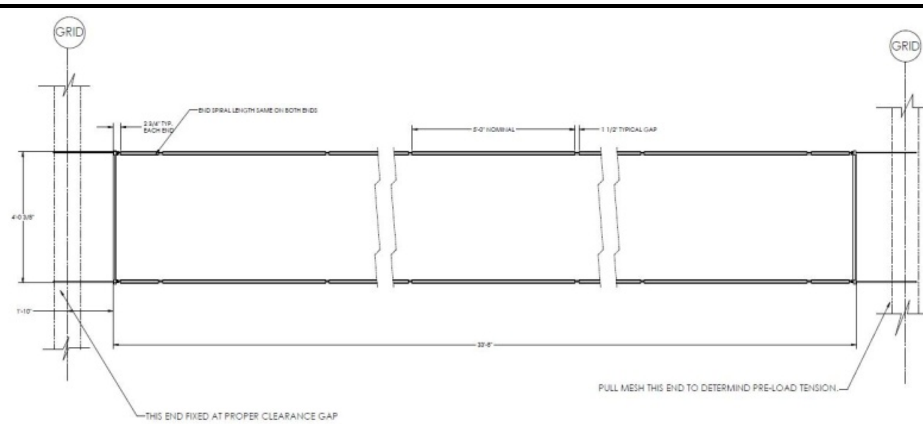
Typical panel system – in this case, four individual panels mounted by cable within a structural frame.



Section view noted above. The deck park panels would be designed in a horizontal, slightly overlapping plane, and not be individually mounted at an angle as in this drawing. No direct sun should penetrate between the deck park panels.



Typical clearance at each end of panel; this must be reduced significantly for the deck park concept – to preclude direct sun penetration at ends of panels.



Drawing of an individual panel; horizontal view of panel between structural grids.

Issues to Consider

More detailed design development of the proposed system will require the following information:

- Actual cad drawings or field measurements of the roadway and immediate area around each tunnel entrance.
- Structural design of a light-weight truss, or similar system capable of the spans required for the shading system, as defined in the BDA Engineers recommendations.
- Structural analysis of the adjacent exit ramps and tunnel entrance for feasibility of mounting of the structural system noted above. (See photos above).
- Clarification of limits or options for placement of structural system adjacent to north side of roadway (south side for eastbound tunnel portal) for westbound portal. Who owns the property and can it be used for this project?
- Other safety and security issues that may be identified for the project.
- Strategies for nighttime lighting of the roadway under the proposed shading system; must use the same spacing pattern as the existing tunnel lighting.
- Actual design of the shading strategy and consultation with the product manufacturer, Cambridge Architectural, on the system. Thorough analysis of maximum panel size will be required to limit potential deflection of the architectural mesh material within the tension cable and structural systems.
- Computer modeling of actual performance of the proposed shading strategy.
- Completion of a design development set of drawings for more accurate cost estimates.

Cost

As noted, the manufacturer has estimated cost at approximately $50.00 per square foot of shading system. This estimate includes the tension cable mounting system but excludes the underlying structural system that will be required to support the shading structure and its long spans. The light-weight structural system, per a preliminary analysis by Greg Bickley, BDA Engineers, is $32.00 TO $40.00 per square foot. Roadway lighting will be required and mounted within the shading structure; estimated at $5.00 per square foot.

Summary

This report recommends further exploration and design of a *slopped, horizontal shading structure* of approximately 40,000 square feet at each the westbound and eastbound portals of the deck park tunnel. The actual area of the shading structure may be less depending on actual site drawings or field measurements and the actual coverage needed for the roadway and the entrance/exit ramps/lanes located at each portal. Finally, it is recommended that the ADOT and project team visit the University of Arizona project as well as other projects located in the Phoenix area to see the actual "shade" product and see how various applications have been designed.

g. Option 4 – Apply a High-Reflectance White Coating to All Ceilings, and Specify a Light-Colored Housing on All New Luminaires

The total amount of illumination that ends-up on the roadway surface is a combination of both the direct illumination from the luminaires, and the indirect illumination that has reflected off of the floor, wall, and ceiling surfaces. As a result, the reflectivity of these surfaces can have a dramatic effect upon the total amount of illumination on the roadway. This is one of the reasons that light-colored ceramic tiles were included in the original design, and also why ADOT endeavors to keep these tiles clean & reflective via the periodic cleaning. The original design for the tunnel did not include a light- colored, highly-reflective finish on the ceilings, but can definitely benefit from such a treatment.

This Option addresses the concept of increasing the reflectivity of the ceiling surfaces by a combination of: applying a long-life, easy-to-clean, white coating with an initial reflectance of 88% that will have to be re-done every 10 years; and specifying new luminaires with a light-colored housing such as white or tan. The estimated implementation cost is based solely upon the installed cost of the white coating, and does not include the cost for any new luminaires, as this is already included in the Revised Base Case.

Option 4 – High-Reflectance White Coating on Ceiling			
		Day	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	181	1.7
Threshold Zone 2nd Half	luminance level	161	2.2
Transition Zone 1	luminance level	50	1.9
Transition Zone 2	luminance level	11	3.1
Transition Zone 3	luminance level	9.0	2.8
Interior Zone	luminance level	9.0	2.5
Implementation Cost (For the application of an 88% reflective white coating to all of the ceilings.)		$725,000	
Yearly Energy Cost		$335,219	
Yearly Maintenance Cost (Includes costs for including the white coating in the periodic Tunnel cleanings.)		$59,000	
Yearly Savings		n/a	
Simple Payback Years		n/a	
25-Year Life-Cycle-Cost Present Value		$11,226,565	

Photo of the Test Area inside the eastbound threshold
where the white coating has been applied to the ceiling
(See Attachment #3)

Photo of the Test Area inside the eastbound threshold that
demonstrates the extreme difference between the reflectance of
the new white coating and that of the existing dark ceiling surface

h. **Option 5 – Revise the Maintenance Procedures to Increase the Luminance Levels with the Existing Luminaires.**

The existing luminance levels are substantially less than those included in the original design documents, and this can be partially compensated for by revising the maintenance procedures.

All HPS lamps degrade in lumen output with age. However, there are lamps available that are designed to produce more lumens than standard lamps when new, and maintaining a higher lumen output over the life of the lamp – effectively providing more light with no increase in energy consumption. These lamps also tend to possess longer field lives than standard lamps, and many do not experience the "cycling" that is normally associated with the end-of-life of HPS lamps. *(See Attachment #4 for an example of a high-lumen HPS lamp)*

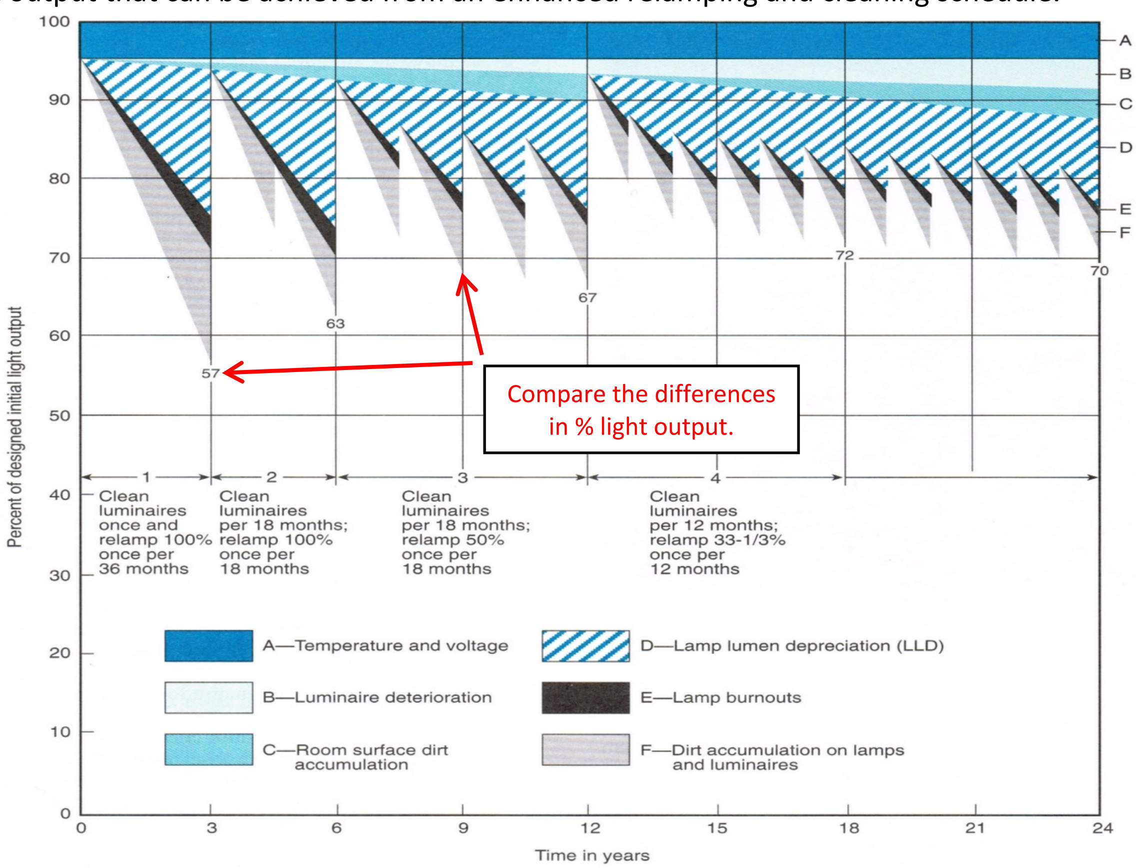
Option 5 – Revise The Maintenance Procedures			
		Day	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	198	1.9
Threshold Zone 2nd Half	luminance level	149	2.0
Transition Zone 1	luminance level	54	2.0
Transition Zone 2	luminance level	11	3.4
Transition Zone 3	luminance level	9.5	3.0
Interior Zone	luminance level	9.4	2.6
Implementation Cost (For the incremental cost of the high-lumen lamps.)		$32,000	
Yearly Energy Cost		$335,219	
Yearly Maintenance Cost (includes the annual incremental cost for the high-lumen lamps. Group-relamping is expected to actually reduce maintenance costs, but this will be balanced against the proposed enhanced cleaning procedure.)		$61,000	
Yearly Savings		n/a	
Simple Payback Years		n/a	
25-Year Life-Cycle-Cost Present Value		$9,854,710	

By the time that an HPS lamp eventually fails, it may have reduced in output to as low as 72% of the initial output (see following Table). Replacing them prior to failure will result in an immediate increase in light levels throughout the tunnel.

Light source	Rated life	Lumen maintenance @ 50% rated life	Lumen maintenance @ 100% rated life
Incandescent	1000	90%	78%
Tungsten-halogen	2000	97%	93%
Fluorescent (medium loading)	20,000	85%	75%
Mercury	24,000	75%	65%
Metal halide	15,000	80%	65%
High pressure sodium	24,000	90%	72%

Life and lumen maintenance data adapted from IESNA Lighting Handbook: Reference and Application, *9th edition (2000).*

The accumulation of dirt, both on and within the luminaires, will have a dramatic impact upon the amount of light output. Addressing this issue, as well as the lumen-degradation issue, would be the primary reasons for implementing a "Group Relamping" program for the tunnel. The concept of Group Relamping involves relamping large sections of the tunnel on a proactive basis, and before the lamps fail, in order to maintain higher average levels of lumen output. An exact schedule would need to be determined, but the Step-A luminaires that operate 24/7 should be relamped twice as often as the others. This process can also involve an enhanced cleaning schedule, where the luminaires are opened at least once per year for a thorough cleaning, and not just a wide-down when a relamping occurs. Group Relamping is also known to reduce lamp and labor costs, as the lamps can now be purchased in bulk, and the amount of labor time per luminaire is reduced since the technicians are now moving between adjacent luminaires, as opposed to widely-spaced luminaires that occurs with spot relamping. The following chart details the increases in light output that can be achieved from an enhanced relamping and cleaning schedule.



i. Option 6 – Upgrade the Lighting Controls

The lighting control system operates by measuring the amount of daylight outside of the tunnel, and responds with increases or decreases in the interior luminance levels, particularly in the Threshold & Transition Zones. This is done in order to try to manage the issue of driver adaptation luminance, and minimize the issues that can result from suddenly leaving bright daylight and entering the darker environment of the tunnel.

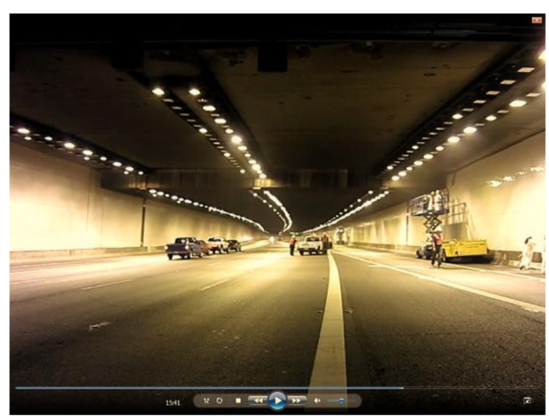
The lighting in the Interior Zone is comprised of two lighting "steps" or groups of luminaires – nighttime (Step A) and daytime (Steps A & B). The Threshold and Transition Zones have five different groups or steps (Steps 1 – 5). Step 1 turns on at sunrise in the eastbound tunnel entrance, with more Steps (groups of luminaires) turning on as the sun rises and the ambient brightness outside the tunnel increases. Then, theoretically, the process reverses itself as the sun rises out of the eastbound drivers' forward line-of-site, until the setting of the sun has the same impact upon the westbound traffic by sinking into their forward line-of-site. Until at sundown, at which time all Steps/groups other than Step A should turn off for the night.

Photos of the lighting control system being operated manually

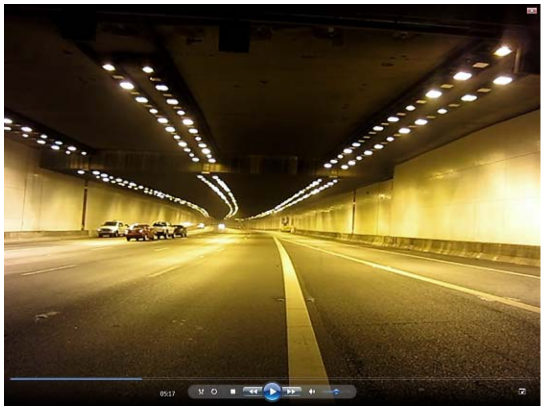
Step A

Step B/1

Step 2



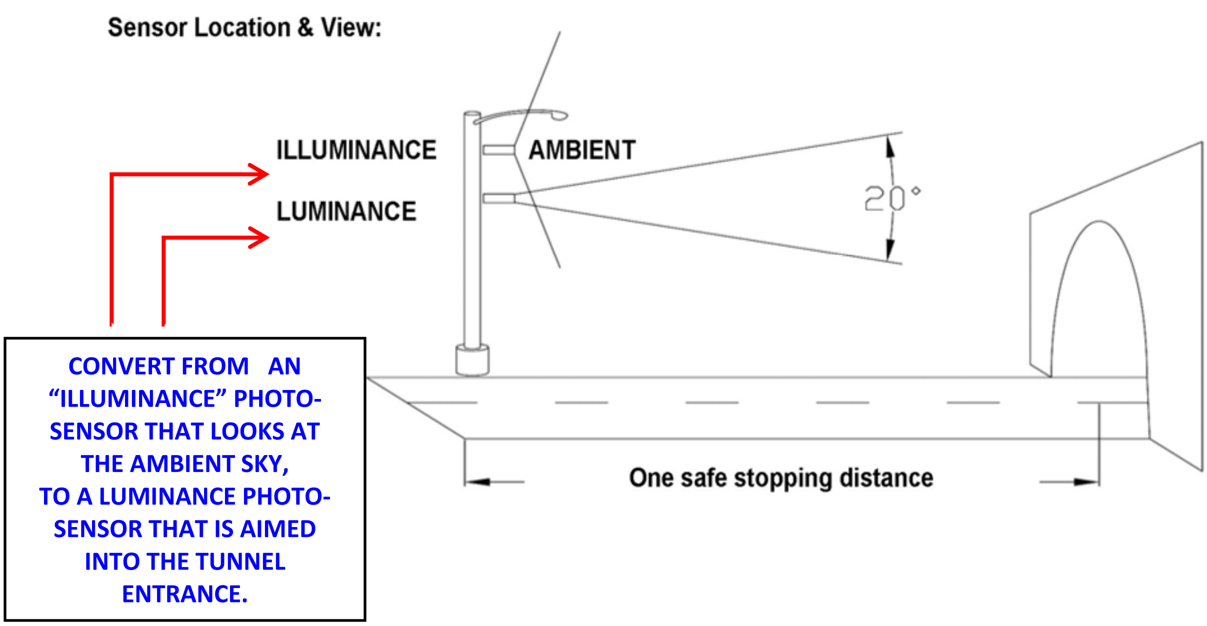
Step 3

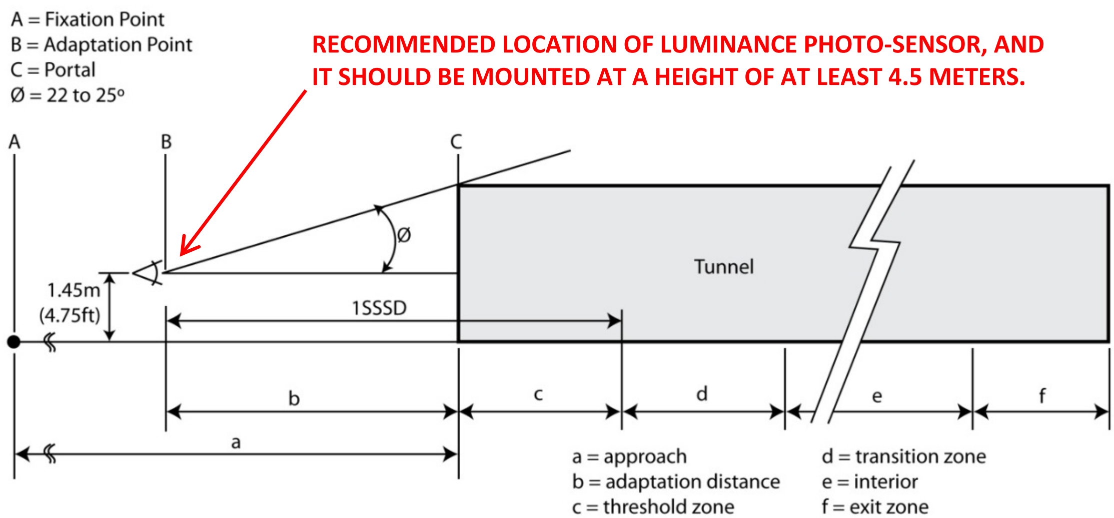


Step 4

Step 5

However, as previously discussed, the existing lighting is not following this expected pattern, but instead appears to be operating with all Steps turned on all day. Part of the reason for this deviation from the expected load profile is due to the low amount of illumination that the luminaires are producing, while the other part is due to not having the optimal types of photo-sensors and associated programming in place. Although lighting design practices for tunnel are based upon luminance (candelas-per-square-meter), the existing photo-sensors are measuring illuminance (footcandles). In addition, the existing photocells are located adjacent to the tunnel entrances, and facing into the sky, whereas they should be located at a distance of one SSSD from the entrances, and aimed into the entrances (like with the luminance meters utilized for the original Lseq testing). Replacing the photocells with luminance units, and locating/aiming them correctly, will greatly increase the accuracy of the measurement function of the control system, and could result in reduced lighting operating hours.





Installing wires to the photo-sensors that are to be located so far from the tunnel entrances could end up being very expensive and involved, and so the use of wireless technology should be considered. This would involve installing a microprocessor unit with an internal transceiver near the locations of the existing photo-sensors, and connecting it to the existing communication wires that lead back to the main control system. The new luminance photo-sensors, which have been located as per industry standards and manufacturer recommendations (see above diagram), will then communicate wirelessly with the microprocessor, which will then transmit upstream to the main control system. *(See Attachments #5 & #6 for examples of luminance photo-sensors and microprocessors that can be customized to communicate wirelessly)*

The last step in the upgrade process is to re-programming the control software, although the controls engineer should be involved in the process from the beginning. In-field testing of the revised luminance levels, at which the various Steps are to turn on and off, should be performed in order to verify the new equipment settings and software programming.

The energy savings that could result from converting a tunnel's control system from illuminance to luminance, is dependent upon many factors, and impossible to accurately predict (especially in this particular situation). However, there have been instances in which the operating hours of the lighting were reduced by 10 – 15%.

Recent improvements in control systems are now allowing for real-time feedback, which can maximize energy-savings by measuring the actual luminance levels in the tunnel, and then turning-off or dimming some of the luminaires even though the master luminance photo-sensor is still signaling for them to be turned on. This type of system works especially well with LED luminaires, as it can ramp each luminaire up or down via dimming or multi-level control.

Option 6 – Upgrade The Lighting Controls			
		Day	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	158	1.5
Threshold Zone 2nd Half	luminance level	119	1.6
Transition Zone 1	luminance level	43	1.6
Transition Zone 2	luminance level	8.8	2.7
Transition Zone 3	luminance level	7.6	2.4
Interior Zone	luminance level	7.5	2.1
Implementation Cost (For the materials and labor costs associated with all of the upgrade steps described in this section.)		$40,000	
Yearly Energy Cost		$305,049	
Yearly Maintenance Cost (includes additional cleaning costs for white coating)		$50,000	
Yearly Savings (It is estimated that the lighting accounts for 90% of the yearly energy cost, and this upgrade could produce a 10% reduction in lighting energy cost.)		**$30,170**	
Simple Payback Years		**1.36**	
25-Year Life-Cycle-Cost Present Value		$9,556,026	

j. Option 7 – Install New High-Efficiency Luminaires

This section will address the concept of replacing the existing HPS luminaires with new luminaires that utilize one of more types of high-efficiency light sources, such as Metal Halide, Induction, and LED. Since the existing luminaires will need to be replaced within the next 5 years anyway, the calculated energy savings from using these nigh-efficiency light sources only needs to off-set the incremental cost between these types of new luminaires, and the replacement HPS luminaires that would be specified under the "Revised Base Case".

As stated previously, the first decision that needs to be made is in regards to the desired L_{TH} value of the renovated lighting. The higher the required L_{TH}, the more likely it is that an analysis is going to favor utilizing high-intensity-discharge (HID) light sources, like HPS and metal halide (MH), in at least the Threshold Zones. LEDs and Induction Lighting are simply not yet powerful enough to replace HID luminaires on a one-for-one basis and achieve high L_{TH} values. In every one of the LED manufacturer submittals, the designer had to utilize a quantity of LED luminaires that was approximately double the quantity of the existing HPS luminaires – in order to achieve the target L_{TH} of 350 cd/m^2. The same trend is apparent in the single Induction Lighting submittal that was received, as the designer prepared their submittal based upon illuminance (footcandles) instead of the specified metric of luminance, and did not utilize any light-loss-factor (LLF) in their calculations. It appears that the Induction Lighting design would actually consume more energy than what would be required by an upgraded HPS design.

<u>Light Emitting Diodes (LEDs)</u>

- Although the lumens-per-watt efficacy of an LED module is still less than that of an HPS lamp, the LED is more efficient at projecting light out of the luminaire, and can therefore often provide 10 – 25% energy savings, depending upon the application.
- The efficiency of LED luminaires have more than doubled since the beginning of 2010, and this trend is expected to continue as the manufacturers become more adept at providing proper thermal management for the new and future generations of high-brightness LED modules.
- The primary mode of energy savings that is available from the use of LED luminaires is the ability to dim or turn them off when they are not needed. This can result in more energy-savings than the 10 – 25% savings available from the increase in overall luminaire efficiency. This ability to dim would lend itself well to the Transition Zones, as well as the Interior Zones, where the same luminaire can be dimmed from daytime to nighttime to luminance levels.
- The performance and photometric distribution varies a great deal from manufacturer to manufacturer, and even from model to model within the same

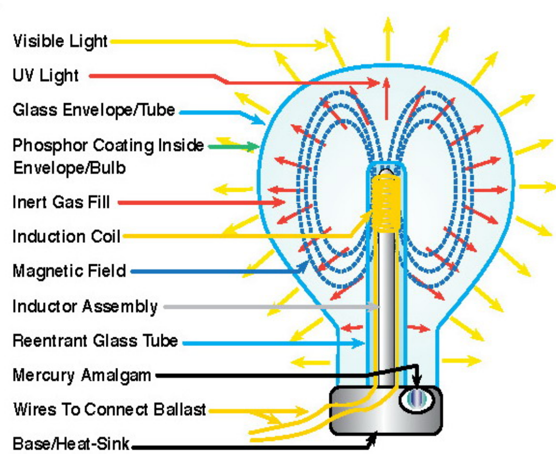
manufacturer. Evaluating LEDs for use on a project must involve detailed photometric analysis.

- The LED modules and drivers/controllers in an LED luminaire are very sensitive to excessive ambient temperatures, which can result in permanent damage to the components. This is why LED luminaires should preferably be designed from scratch, as opposed to some of the lower cost luminaires where LED modules have been built into housings originally designed for HID lamps.
- There are some satisfactory LED retrofit modules available on the market, but the exact module/luminaire combination should undergo a thermal test prior to installation of even a test area.
- Industry standards require that all types of luminaires undergo heat testing at 25°C, but this is insufficient for use in Arizona. Only luminaires that have been tested at a minimum of 40°C (and preferably higher) should be considered for outdoor use in Arizona.
- As a result of industry consensus, the rated life of an LED luminaire is considered to be the point at which the light output degrades to 70% of the initial light output. This is referred to as the L-70 standard, and is detailed in the IESNA document LM-79 "Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products". Prospective suppliers should be prepared to discuss their methods for compliance with this standard, as well as their methods for compliance with IESNA LM-80 "Approved Method for Measuring Lumen Maintenance of LED Light Sources", and IESNA TM-21 "Projecting Long Term Lumen Maintenance of LED Light Sources".
- Many LED luminaires are listed with a field life of 70,000 – 100,000 hours , but this is often only valid for an ambient temperature of 25°C, and/or with a particular combination of LED module, driver, or operating current. Some manufacturers offer different operating currents for each of their luminaires, as the higher currents provide more light from the same LED modules, but the trade-off is reduced field life. It should also be noted that a life rating of 100,000 hours only translates into about 11 years for the Step A luminaires that operate 24/7, and about twice that length for the other luminaires/Steps. The luminaires may keep operating beyond this point, but the light output will be less than that recommended by the L-70 standard.
- Luminaires being considered for use should preferably be EnergyStar rated, or at least approved by the Design Lights Consortium. If they have not yet been approved by EnergyStar, they should at least be able to pass the Fitted Target Efficiency (FTE) test, which consists of a free software package available for download from: http://www1.eere.energy.gov/femp/technologies/ssl_resources.html#fitted
- Model Specifications for LED Roadway Lighting have recently been issued by the Municipal Solid State Lighting Consortium, and can be downloaded from this site: http://www1.eere.energy.gov/buildings/ssl/consortium.html

- A well-designed luminaire will appear to be mostly vanes/ribs or other physical strategies for the passive rejection of heat, should locate the internal driver/controller in a location where it will not receive excessive radiated heat from the LEDs, and should allow for the in-place replacement of the LED modules/bars. These are luminaires on the market that require the entire light engine to be replaced in order to replace a single failed LED.
- *Examples of LED luminaires that are available for tunnel applications can be found in Attachments #7 – 10.*

Induction Lighting

- Induction lighting does not utilize cathodes, arc tubes, or filaments to generate light, but instead consists of an magnetic coil, mounted on an "antennae" that is located within a glass vessel that is coated on the inside with fluorescent-style phosphor. An electronic generator device (akin to a driver or ballasts) induces the coil to produce an intense magnetic field in the MHz or GHz range, which interacts with the mercury amalgam within the vessel. As with a fluorescent lamp, the "excited" mercury atoms produce radiation that strikes the phosphor on the glass vessel, which reacts with then energy and generates visible light. This is why the light produced by an induction lamp has a fluorescent-like quality.



Philips Lighting – "QL" Induction System

- Induction lighting has a lower lumens-per-watt efficacy than HPS or new-generation fluorescent, but is notable for its longevity. As there are no cathodes or arc tubes to fail, the glass vessel is rated for 100,000 hours. However, many of the generators are only rated for a field life of 60,000 hours, and so this becomes the realistic field life of the components, as most technicians will replace the vessel as long as they already have to replace the generator and antennae.

- The generators are as sensitive to ambient heat as any other type of electronic component, and so care must be taken in the design of any luminaires that are to be used outdoors. The major manufacturers of the vessel-antennae-generator system (Philips and Sylvania) even require that a potential luminaire be submitted to them for review & approval before they will warranty their system in a particular luminaire. This is also why these two manufacturers will generally not warranty a system that has been retrofit into an existing luminaire.
- Induction has been used for many parking structure applications that desire "white light", but wish to avoid the need to relamp every one to two years.
- The "vessel" that actually generates the light is much larger than the arc tube of an HID lamp, which results in the light produced being difficult to control and shape into efficient photometric patterns. As a result, induction luminaires can have difficulty producing the same high levels on a task as is available from HID light sources, and some induction luminaires, even those being marketing for roadway lighting, have difficulty achieving the IESNA-recommended uniformity ratios.
- Just as with many LED luminaires, many Induction luminaires are marketed as a way to save energy because the S/P ratio (blue-rich content) of the light produced is supposed to provide better visibility conditions, lumen-for-lumen, at nighttime. The cutsheets for these products list one value for the photopic lumens (daytime vision), and a much higher value for the scotopic lumens (nighttime vision in very dark areas), and then try to utilize the scotopic lumen value in their photometric studies. This is generally not considered to be a valid approach, as unless the light level to be produced is very low, such as with residential street lighting or the nighttime lighting level in the tunnel's Interior Zone, the photometric calculations should be based upon photopic lumens.
- The other major advantage over HID light sources is that the system is instant-on after a power outage or equipment failure. This characteristic should be of particular value to ADOT for use at the Deck Park Tunnel. Not only for the of quick restoration of full lighting after an outage, but also due to the fact that it could dramatically reduce the energy consumption of the emergency lighting system, which is comprised of Tunnel Guard luminaires with HPS lamps. Because even a power interruption of less than one second can extinguish an HPS lamp (which results in darkness for several minutes while the lamps cools down, restrikes, and then warms back up) the emergency lighting in the tunnel operates 24/7 and is supplied by costly-to-maintain UPS systems. Therefore, converting the emergency lighting to induction, and re-wiring as necessary so that the luminaires do not come on except during an actual emergency, will save a substantial amount of energy and maintenance costs, as the emergency lighting can then be operated directly off of the emergency generator. It should be noted however, that the NEC and NFPA codes have been revised several times since the tunnel was completed, and the existing luminaire locations may not provide the quantity and uniformity of illumination required by the current version of the codes.

- Specifying a luminaire with an induction lighting system is generally a $200 - $300 adder, and so this system is usually reserved for lighting applications that will be difficult or expensive to maintain.
- *An example of an Induction luminaire that is available for tunnel applications can be found in Attachment #11.*

Metal Halide with an Electronic Ballast

- Large advances have been achieved with the efficiency and field life of metal halide lamps – particularly a new generation of lamps that has been designed for exclusive operation on electronic ballasts. This new series of lamps utilizes pulse-start technology for improved lumen maintenance over life, and ceramic arc tubes for increased efficiency, improved color, and quicker warm-up & re-strike.
- The addition of a modern electronic ballast results in a lighting system that operates at efficacy ratings and lumen outputs close to that of HPS. Therefore, if a particular application were to require very high light levels, such as the Threshold Zone of a tunnel, this amount of light can be produced with less wattage, and with a lower up-front cost, than available with either LED or induction.
- Some of these lamps are rated at 30,000 hours life when operated on an electronic ballasts, which is 25% longer than the life of a standard HPS lamp.
- Some of the new electronic ballasts can provide bi-level or multi-level operation, which can be extremely useful in the Threshold and Transition Zones.
- The most cost-effective and energy-efficient option for lighting the Deck Park Tunnel is likely a combination system, consisting of electronically-ballasted metal halide luminaires in the Threshold and Transition Zones (Steps 2 – 5), and LED or Induction luminaires for use throughout the tunnel (Steps A & B).

The next generation of white light

Philips MasterColor CDM Elite MW System. The medium wattage CDM lighting system that gives superior, long-lasting white light for both indoor and outdoor use.

Product Number	Lamp Ordering Code	Nom. Watts	ANSI Code	Approx. Initial Lumens[1]	Approx. Mean Lumens[2]	Efficacy (lm/w)	Color Temp. (Kelvin)	CRI	Burn Position	Rated Avg. Life (Hrs.)[3]	Lumen Maint. 20khr (%)
22062-4	CDM Elite MW 210/T9/930/U/E	210	C183/E	24,150	21,735	115	3000	90	Universal	27,000	80
21831-3	CDM Elite MW 315/T9/930/U/E	315	C182/E	38,700	34,440	123	3000	90	Universal	30,000	80
22063-2	CDM Elite MW 210/T9/942/U/E	210	C183/E	23,000	20,470	110	4200	90	Universal	30,000	80
22064-0	CDM Elite MW 315/T9/942/U/E	315	C182/E	35,500	31,150	113	4200	90	Universal	30,000	80
23806-3	CDM Elite MW 210/T12/930/U/O	210	C183/O	23,300	21,600	111	3000	90	Universal	20,000	80
23807-1	CDM Elite MW 315/T12/930/U/O	315	C182/O	36,200	31,500	115	3000	90	Universal	20,000	80
23808-9	CDM Elite MW 210/T12/942/U/O	210	C183/O	22,800	20,500	109	4200	90	Universal	20,000	80
23809-7	CDM Elite MW 315/T12/942/U/O	315	C182/O	34,300	30,780	109	4200	90	Universal	20,000	80

All lamps are dimmable to 50% power (0-10V).

Option 7 – Install High-Efficiency Luminaires			
	LED Only	**Induction Only**	**Metal Halide in combination with LED or Induction**

(Since this will be a complete redesign, it is presumed that the resulting luminance levels will be the same, regardless of the technologies utilized. However, the uniformity ratios will be different, and cannot be finalized without a complete design)

		Day	**Night**
Threshold Zone 1st Half	luminance level (cd/m^2)	350	2.5
Threshold Zone 2nd Half	luminance level	245	2.5
Transition Zone 1	luminance level	96	2.5
Transition Zone 2	luminance level	39	2.5
Transition Zone 3	luminance level	24	2.5
Interior Zone	luminance level	11	2.5

	LED Only	Induction Only	Metal Halide in combination with LED or Induction
Implementation Cost (It is presumed that a complete new lighting system will be designed in conformance with the luminance levels recommended by RP-22-11, and so that cost represents the incremental cost between implementing Option 1, and the new luminaire options described in this section.)	$4,200,000	$3,400,000	$2,100,000
Yearly Energy Cost (It is estimated that the lighting accounts for 90% of the yearly energy cost. and this upgrade could produce energy savings AS COMPARED TO IMPLEMENTING OPTION 1. Complete designs would need to be performed in order to finalize the estimated energy savings.)	$618,616	$795,148	$556,754
Yearly Maintenance Cost (Estimated cost for the 25-year life of the analysis, allocated over the 25-years.)	$84,000	$24,000	$75,000
Yearly ENERGY Savings (AS COMPARED TO IMPLEMENTING OPTION 1.)	$135,974	-$40,738	$166,815
Simple Payback Years	30.89	n/a	12.59
25-Year Life-Cycle-Cost Present Value	$16,506,897	$17,506,898	$13,392,740

III. Acknowledgements

REFERENCES & TECHNICAL ASSISTANCE

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IES Lighting Handbook 9th Edition

International Commission on Illumination (CIE)
CIE-88 (2004)

Burgess & Niple
Tempe, Arizona

Schréder Lighting, LLC - The Right Light
http://schreder.us/

IV. Appendices