GEORGIA DOT RESEARCH PROJECT 22-31

Final Report

DAYTIME LIGHTING IN SHORT TUNNELS

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16. Abstract

Daytime lighting is warranted when natural sunlight fails to provide sufficient visibility for tunnel users. According to the American Association of State Highway Transportation Officials (AASHTO) *Roadway Lighting Design Guide*, no supplemental lighting is required if the tunnel is less than 80 ft in length, whereas supplemental lighting is needed if the tunnel length exceeds 410 ft. However, inadequate guidance is provided for the interim tunnel lengths (i.e., 80 ft ≤ tunnel length ≤ 410 ft). As such, for the short tunnels in this particular range, specific guidelines are necessary for daytime lighting warrant analysis and determination of the low-visibility area for lighting installation. In addition to the tunnel length, visibility in short tunnels is dependent on a variety of factors, including tunnel type, light penetration, median wall presence and type, orientation, whether the tunnel is straight or curved, reflectivity of pavement and interior surfaces, etc. Short tunnels, particularly on clear and sunny days, may experience visibility challenges due to the significant contrast in luminance between the tunnel interior and the exterior environment. This stark difference can create a "black hole" or "black frame" effect, temporarily blinding drivers and impeding their ability to detect potential hazards or small objects within the tunnel. To better understand this problem and address the associated safety concerns, field measurements of luminance and illuminance have been conducted for a number of short tunnels in Georgia. This research study leveraged this invaluable dataset to develop an analytical process consisting of decision trees and regression models aimed at achieving two primary objectives: (1) correlate adequate visibility and daytime lighting in short tunnels by evaluating the key variables, and (2) identify the specific areas within a tunnel that need artificial illumination. However, it is important to note that the conclusions and suggestions outlined in this study are tailored to tunnels falling within the restricted length range of 80 to 250 feet. This limitation stems from the dataset's constraint, encompassing tunnels strictly below the 250-foot threshold. A more inclusive and comprehensive investigation is needed to incorporate an expanded dataset covering the entire spectrum of short tunnels, including those up to 410 feet in length.

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GDOT Research Project 22-31

Final Report

DAYTIME LIGHTING IN SHORT TUNNELS

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Safe and efficient travel through short tunnels is paramount, and appropriate lighting can be a key factor in achieving this goal. While guidelines exist for very short (<80 ft) and long (>410 ft) tunnels, there is a critical gap concerning tunnels with lengths falling in between (80–410 ft). This research project seeks to address this knowledge gap by developing specific guidelines for the evaluation and integration of daytime lighting for short tunnels. Field measurements of luminance and illuminance, as well as visibility observations, were conducted for a variety of short tunnels in Georgia. These field measurements and observations were utilized to:

- Construct a decision tree for daytime lighting warrant analysis.
- Develop a practical method for delineation of the poor visible zone within a short tunnel necessitating daytime illumination. Specifically, we developed regression models structured as power functions for different tunnel clusters to capture distinct light penetration patterns. By employing these cluster-based models in conjunction with a defined appropriate illuminance threshold, enabled the poor invisible zone to be located.
- Formulate and solve an optimization problem by which the optimal horizontal illuminance threshold value of 46 fc was established.

By leveraging the field data and advanced modeling, this research study establishes a practical process for evaluating and implementing daytime lighting in short tunnels. However, it is important to note the limitations inherent in the data utilized for this study. Specifically, the dataset comprises tunnels of less than 250 feet in length, predominantly consisting of span type tunnels. Notably, only four culvert tunnels were initially included, yet due to their ambiguous characteristics in comparison to span tunnels, these culverts were excluded as part of the data curation process. These limitations may potentially result in biased models that struggle to generalize effectively, particularly when applied to new tunnel scenarios. Addressing these limitations requires further investigation. To enhance the reliability of the recommended process, future studies could greatly benefit from implementing a physics-guided machine learning approach, coupled with an expanded and more comprehensive dataset.

CHAPTER 1. INTRODUCTION

The purpose of daytime tunnel lighting is to increase visual acuity outside and inside a tunnel to ensure that motorists can safely approach, enter, and pass through the tunnel at the design or posted speed. For short tunnels (<410 ft), sunlight can sometimes sufficiently penetrate the interior such that daytime lighting is not necessary. However, this may not always hold true, depending on many other factors, including the type of tunnel (e.g., span or culvert), portal height, tunnel width and length, tunnel orientation, and median presence and type (e.g., wall versus pier), among others. The need for daytime lighting guidelines in short tunnels spanning from 80 to 410 ft is underscored by the *Roadway Lighting Design Guide* (American Association of State Highway and Transportation Officials [AASHTO] 2018). Presently, the guidelines identify a number of factors, including expected traffic, cyclist activity, tunnel curvature, daylight penetration, and interior surface reflectivity. It stipulates that additional lighting is not necessary for tunnels less than 80 ft and that it is required for those exceeding 410 ft, leaving a gap for tunnels with lengths falling between 80 and 410 ft. Notably, the 80-ft threshold is relatively consistent with the rule of thumb that short tunnels with length under 5 times the portal height would not need lighting. This is based on the assumption that daylight sufficient to support driver visibility extends 1.5 times the average height of the entrance portal into the tunnel and 3 times the height from the exit (Gibbons et al. 2023).

Previous research concerning vehicular safety within tunnels has shown that accident rates are notably higher in shorter tunnels as compared to longer ones (figure 1). More specifically, these accident rates tend to peak in the initial sections of tunnels (particularly in the threshold and transition zones) and decrease as drivers continue driving inside the tunnel and experience eye adaptation to the lower light levels.

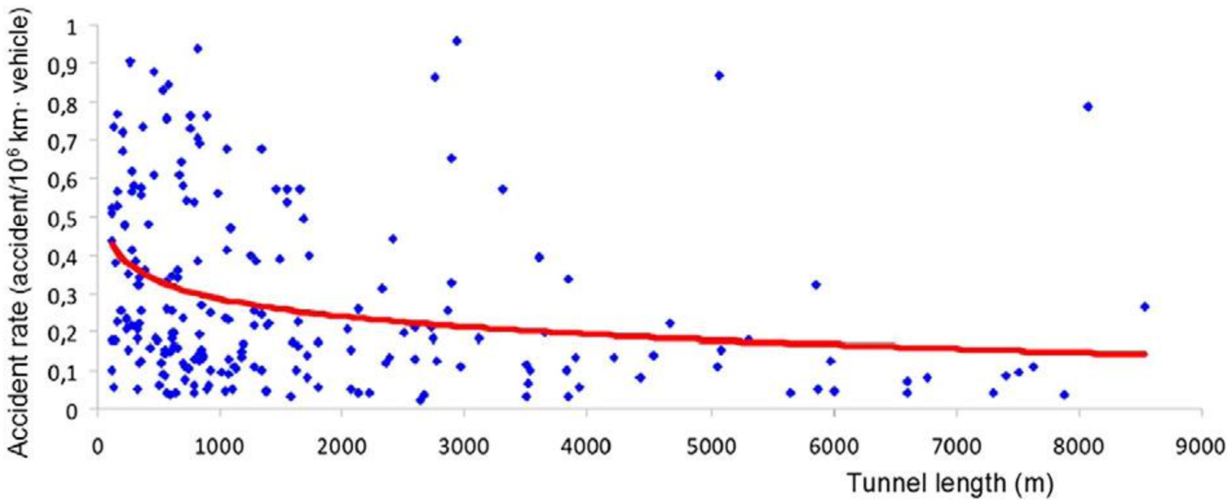


Figure 1. Graph. Trend line and scatter plot of tunnel length versus crash rate, excluding tunnels without crashes (Anundsen and Engebretsen 2009).

The primary external and internal areas associated with and affected by tunnel lighting design are shown in figure 2. The higher risk in the threshold and transition zones (indicated by "c" and "d" in figure 2) is largely due to the fact that drivers entering a tunnel during daylight have a short time to adapt to the relatively dark surrounding in the tunnel, necessitating gradual reduction of tunnel lighting in the threshold and transition zones of the tunnel (Bassan 2016). Depending on the posted speed, short tunnels because of their length may only have a threshold zone (AASHTO 2018). As shown in figure 2, the length of the threshold zone "c" can be computed by eq. 1.

$$c = 1SSD - b \tag{1}$$

where,

$1SSD = 1\ stopping\ sight\ distance$

$b = \frac{m - 4.75}{tan\phi}$, where m is portal height in ft.; ϕ is the vehicle windshield cut-off angle, which is typically in the range of 22° to 25°.

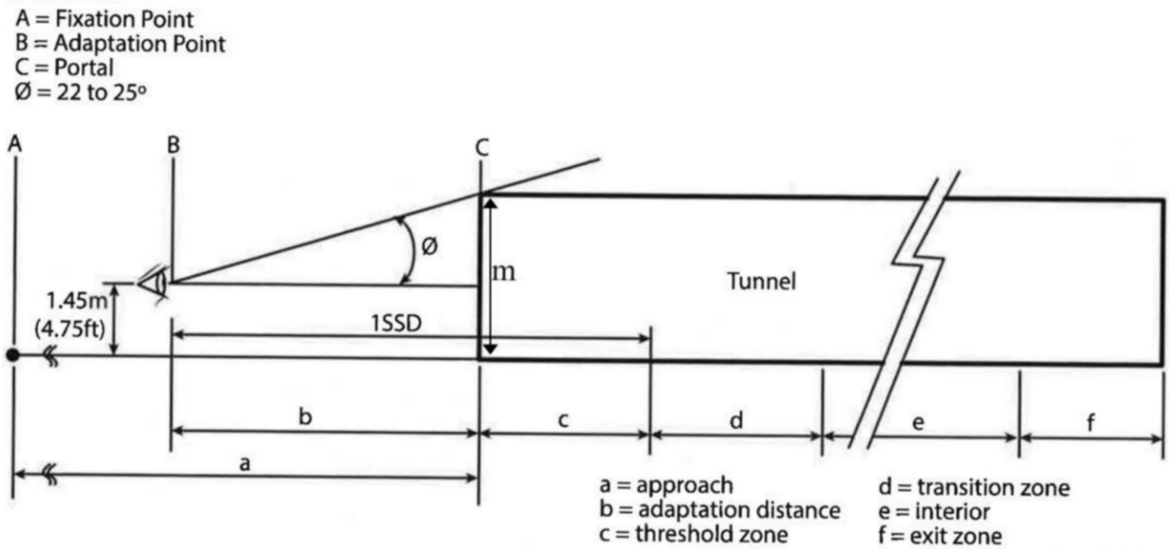
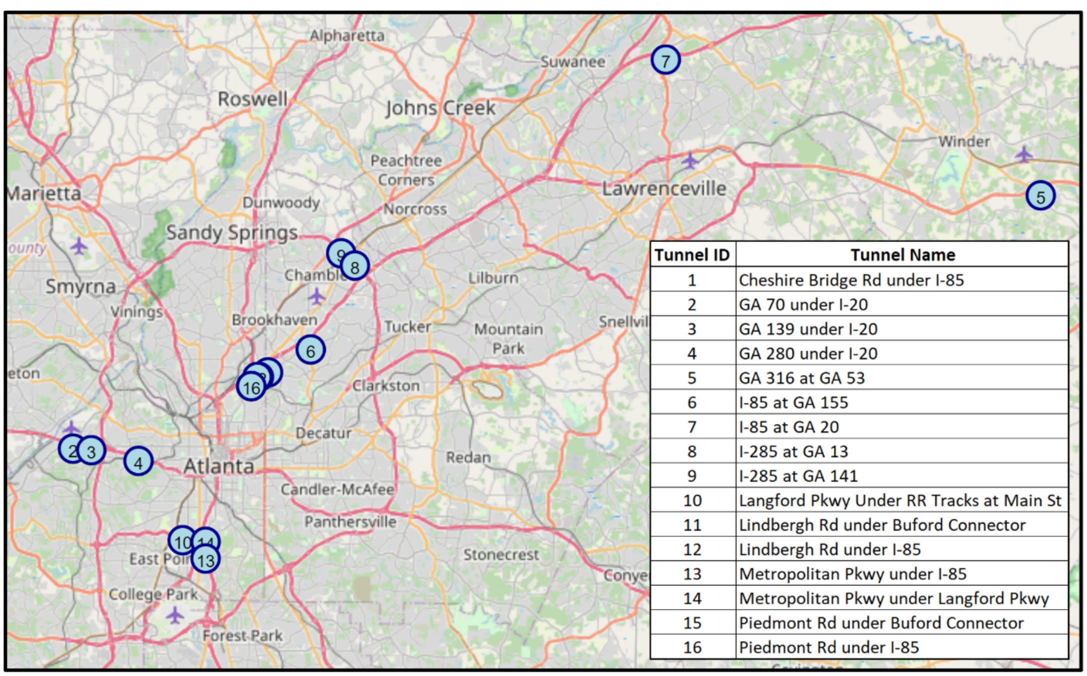


Figure 2. Diagram. Primary external and internal areas associated with and affected by tunnel lighting design, adapted from the Illuminating Engineering Society (IES RP-8 2021).

The Georgia Department of Transportation (GDOT) has previously performed field assessments on 16 short tunnels throughout Georgia, with detailed measurements on illuminance and luminance along each tunnel. The locations of these tunnels are shown in Figure 3.



Tunnel ID	Tunnel Name
1	Cheshire Bridge Rd under I-85
2	GA 70 under I-20
3	GA 139 under I-20
4	GA 280 under I-20
5	GA 316 at GA 53
6	I-85 at GA 155
7	I-85 at GA 20
8	I-285 at GA 13
9	I-285 at GA 141
10	Langford Pkwy Under RR Tracks at Main St
11	Lindbergh Rd under Buford Connector
12	Lindbergh Rd under I-85
13	Metropolitan Pkwy under I-85
14	Metropolitan Pkwy under Langford Pkwy
15	Piedmont Rd under Buford Connector
16	Piedmont Rd under I-85

Figure 3. Map. Locations of the tunnels with field data.

Specifically, measurements of horizontal and vertical illuminances were made every 10 ft within the tunnel, starting from the entrance portal. Likewise, luminance was assessed every 25 ft starting from the entrance portal.

In addition to the illuminance and luminance data, invisible areas were located by setting up visibility targets (1 ft × 1 ft gray boards) throughout each tunnel and subjectively viewed 1 Stopping Sight Distance back from the tunnel portal. The location of these gray cards was referenced to determine the *invisible zone* or zone of unacceptably low visibility existed and if so, where it existed within the tunnel. The investigation found that the tunnel width and height play significant roles in determining visibility conditions within a tunnel. Factors such as the percentage of openings in the tunnel walls and the existence of median piers affect the penetration of natural daylight, and, in other words, the tunnel's internal visibility. The findings from this visibility test align well with the measured values of illuminance within the tunnels.

Specifically, the observed low visibility zones match reasonably well with the areas where measured horizontal illuminance values fell below 50 fc.

While the presence and length of the invisible zone may not be a significant factor in deciding whether daytime lighting is necessary, it is crucial in determining the least amount of artificial daytime lighting needed, if any, to enhance tunnel safety. Hence, the invisible zone, influenced by tunnel design and other factors, should be properly identified. The size of the invisible zone, in combination with other operational conditions (e.g., traffic volumes, posted speed), dictates the risk exposure of tunnel users and should be considered when formulating specific daytime lighting guidelines.

As we delve further into the intricacies, as showcased in figure 2, it becomes evident that portal height (m) and design speed (to compute SSD), plays a critical role in defining visibility standards, particularly in shorter tunnels. This project meticulously analyzed field data on lighting and visibility to develop practical guidelines for daytime lighting to ensure adequate visibility in shorter tunnels.

Notably, short tunnels share visibility issues with their longer counterparts, especially during sunny days when the luminance differential at the entrance portal inside and outside the tunnel is substantial. This can cause the “black hole” or “black frame” effect, impairing drivers’ ability to detect potential obstacles within the tunnel. To gauge the necessity for daytime lighting accurately, one must consider several factors beyond just the length of the tunnel. Figure 4 illustrates the significant role played by the type of tunnel in determining the need for daytime lighting. For instance, span tunnels typically allow more sunlight penetration compared to culvert tunnels. Also, the design of the median, such as the presence of piers, can be an important factor for visibility within the tunnel, a factor not thoroughly addressed in the current ANSI[1]/IES RP-8-22 (IES 2021) guidelines. These guidelines may lead to decisions that contradict human visual expectations. For example, in figure 4, lighting would be recommended for the span tunnel depicted on the left but not for the culvert tunnel on the right. This contradiction emphasizes the need for more elaborate lighting guidelines for short tunnels.

[1] American National Standards Institute.

(a) Span tunnel with median piers (b) Culvert tunnel

Figure 4. Photos. Visual visibility comparison: (a) span versus (b) culvert tunnels.

To establish practical daytime lighting guidelines for shorter tunnels, a two-step decision process is considered in this study: (1) evaluating whether daytime lighting is warranted, and (2) delineating the area for lighting installation if warranted.

CHAPTER 2. LITERATURE REVIEW

Ensuring adequate lighting within tunnels is a pivotal factor that significantly impacts the safety and comfort of road users. Notably, the inclusion of daytime lighting in shorter tunnels, i.e., those spanning between 80 ft and 410 ft, has remained an area lacking comprehensive guidance. Various international and national organizations established guidelines and standards to ensure safety by maintaining a uniform level of luminance, reducing glare, and facilitating the easy adaptation of the human eye from daylight to artificial lighting and vice versa (Hargroves and Lamb 1989).

In the early stages of tunnel lighting research, distinctions were introduced to address the specific needs of different tunnel lengths, as documented in the publication by the Netherlands Foundation on Illumination (NSVV 1963) that laid the groundwork for further studies and advancements in the field. Recently, adaptive lighting systems have been developed to dynamically adjust lighting levels based on external conditions, ensuring optimal visibility at all times (Hu et al. 2019).

The Colorado Department of Transportation (CDOT 2020) lighting design guidelines emphasize the need for specialized lighting in tunnels over 150 ft, with reference to ANSI/IES RP-8-22, Chapter 14. It highlights criteria for lighting design, including traffic direction and emergency lighting considerations, albeit noting the non-adoption of National Fire Protection Association (NFPA) 502: *Standard for Road Tunnels, Bridges, and Other Limited Access Highways*.

The Ohio Department of Transportation (ODOT 2023) established criteria for determining the need for daytime lighting in short tunnels, as outlined in their *Traffic Engineering Manual*. The decision to install daytime lighting is based on two primary factors: the approach speed and the visible proportion of the exit portal area in relation to the entrance portal area from the driver's perspective. This process involves (1) placing the driver no closer than one stopping sight distance from the entrance portal, (2) creating a perspective drawing from the driver's point of view that shows both the entrance and exit portals, and (3) calculating the visible area ratio of the exit portal to the entrance portal from this drawing. Then, the decision on daytime lighting warrant is made based on whether the approach speed is less than 35 mph or not. For approach speeds less than 35 mph, if the exit portal area is less than 50 percent of the entrance portal, daytime lighting is required. For approach speeds of 35 mph or more, if the exit portal is less than 80 percent of the entrance portal area, daytime lighting should be installed.

The Federal Highway Administration's (FHWA) *Lighting Handbook* (Gibbons et al. 2023) indicates that daylight sufficient for driver visibility extends 1.5 times the average height of the entrance portal into the tunnel and 3 times the height from the exit. Short tunnels with a length less than 5 times the portal height might not require daytime lighting. RP-8-22 discusses underpasses and tunnels and provides recommendations on adjusting threshold illumination based on the consideration that dark areas exist for drivers in tunnels during the daytime. An illuminance threshold would greatly benefit the process of designing daytime lighting. Additionally, lighting design for tunnels includes a recommendation that the emergency illumination be consistent with NFPA 502.

Furthermore, considering natural daylight as part of tunnel lighting design or operation has been seen as a sustainable approach that can potentially reduce energy consumption and maintenance costs. It is essential to consider the guidelines set by various organizations, including the International Commission on Lighting (CIE), British Standards Institute (BSI), and World Road Association (PIARC), which offer detailed insights into different aspects such as entrance lighting, veiling luminance, and emergency lighting, among others. These guidelines serve as a basis for national codes and were adapted based on regional experiences and requirements (Hargroves and

Lamb 1989). Hirakawa et al. (2014) confirmed that tunnel lighting can maintain visibility while reducing road surface luminance and saving energy. Moreover, a study by Qin et al. (2017) proposed an energy-saving control system for highway tunnel lighting, which demonstrated a reduction in electric energy consumption. Zhao et al. (2021) developed a tunnel lighting energy conservation algorithm that can save up to 31.40 percent of energy on cloudy days compared to traditional lighting design.

Technological innovations have also played a pivotal role in advancing tunnel lighting systems. Ceriotti et al. (2011) highlighted that wireless sensor networks for adaptive lighting can dynamically match lighting levels to environmental conditions, improving tunnel safety and reducing power consumption. Wang et al. (2020) demonstrated that an intelligent control system can meet the illumination requirements in a tunnel while having a notable energy-saving effect.

In summary, the installation of daytime lighting in short tunnels necessitates careful consideration of various factors, including technological advancements, safety standards, and sustainability. By adhering to established guidelines and leveraging modern technologies, cost-effective and efficient lighting solutions can be developed for short tunnels.

CHAPTER 3. FIELD MEASUREMENT AND DATA PROCESSING

In this project, we obtained field data collected from 19 short tunnels (16 in Georgia, 2 in Illinois, and 1 in Iowa). This dataset contains tunnel features, including tunnel type (span and culvert), tunnel width, portal height, median type (presence of piers), outside structure (piers or walls), outside paved slope, tunnel length, as well as luminance and illuminance measurements along the tunnels. All these tunnel features more or less influence how much natural daylight can penetrate tunnels. Besides tunnel features, we manually collected data on pavement types, i.e., asphalt or concrete, since each type has different reflectivity properties that affect the level of brightness inside a tunnel (Gibbons et al. 2023). It should be noted that this dataset is quite limited given the number of features to consider in relative to the number of tunnels measured in the field. Additionally, all tunnels are relatively short and less than 250 ft and there are only four “culvert” tunnels, which have ambiguous features in contrast with span tunnels.

The luminance values within each tunnel were meticulously measured at a height of approximately 0.5 ft above the ground at intervals of 25 ft. Horizontal and vertical illuminance values were recorded at ground level and 5 ft above the ground, respectively, at 10-ft intervals. These measurements provide a comprehensive view of luminance and illuminance levels throughout each tunnel.

Field observations were conducted to determine the extent of the invisible zone within each tunnel. This involved placing 1-ft-square gray boards on the tunnel floor and assessing whether observers can discern the boards from a distance of 1 SSD, as depicted in figure 5. The real-world observations capture the actual visibility conditions within each tunnel, enabling the team to establish a correlation between actual observed visibility and tunnel characteristics.

Figure 5. Photos. Visibility observations in the field.

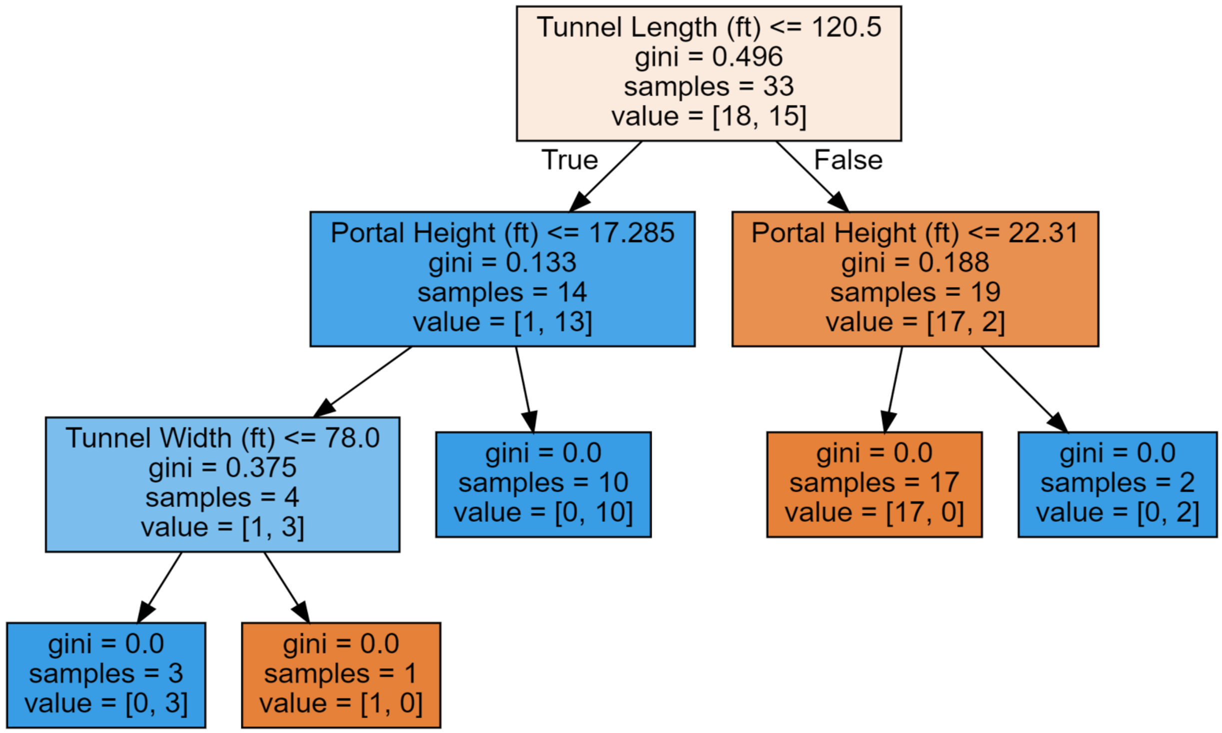
This invaluable dataset serves as the foundation for our in-depth analysis to gain insight into various circumstances in which daytime lighting may be needed for short tunnels. The visibility task is a key variable in establishing adequate safety performance and the 1-foot square target was deemed an obstacle size large enough to demand driver recognition.

CHAPTER 4. WARRANT ANALYSIS FOR DAYLIGHT LIGHTING

Determining the warrant conditions for daytime lighting can be conceptualized as a binary classification problem (i.e., to light or not to light), which can be addressed through a variety of statistical and machine learning (ML) methods. These methods include, but are not limited to, regularized logistic regression, support vector machines, decision trees, etc. Such methods can reveal the inherent relationships between the tunnel features and the visibility observations made in the field. To tackle potential concerns stemming from the scarcity of field data, the research team harnessed ML techniques specifically for small datasets, such as regularization and leave-one-out cross-validation. Regularization yields more efficient models, while cross-validation maximizes the use of limited data. At present, the most promising modeling approach, as per our analysis, is decision trees.

A decision tree, as illustrated in figure 5 is a supervised ML algorithm that can be effectively used for both classification and regression tasks. It is a tree-like structure in which each internal node represents a condition test on a feature (attribute), each branch represents an outcome of that test, and each leaf node represents a class label for the classification task or a numerical value for the regression task. For inference, one starts at the root node and follows the branches based on the condition test until a leaf node is reached, which provides the final prediction. Decision trees mimic human reasoning and are easy to interpret and visualize.

In this study, a binary classification tree was constructed by splitting tunnel features (attributes) to predict if an invisible zone exists based on the visibility observations conducted in the field (figure 6).



Notes:

1) The dark orange color indicates tunnels with invisible zones, while the dark blue color denotes tunnels without invisible zones. The gradient color in between indicates the degree of each node or leaf falling between the two extreme cases. For example, the root node (top node) shows light orange color, indicating majority of tunnels (18 by direction) have invisible zones while other tunnels are visible.
2) gini – refers to gini index or gini impurity, which measures the impurity of a node or leaf in decision trees. It has been commonly used to indicate the quality of a node split when constructing decision trees.

Figure 6. Chart. Construction of the decision tree.

As part of the modeling experiments, each tunnel was annotated by direction regarding the existence of an invisible zone. A data curation process was utilized to ensure data integrity and eliminate some confusing instances with feature ambiguity or blending. This process led to the four culvert tunnels in the dataset being excluded. For this binary classification problem, a tunnel direction is labeled as “invisible” if there is an invisible zone. Otherwise, it is labeled as “visible.” As a result of the data curation process, the initial dataset has a class imbalance, with a significant majority of tunnels featuring an invisible zone, which is expected because the field data collection was focused on those tunnels with an invisible zone. To rectify this data disparity, we implemented a data augmentation procedure to add “interior” points, ultimately achieving a more balanced dataset comprising a total of 33 data points. Considering the small dataset, we chose the leave-one-out cross-validation strategy to maximize data efficiency. This strategy involved leaving a single data point from the original sample for validation and using the remaining data for training. This process was repeated for each data point in the sample. With this approach, we attained an average accuracy of 91 percent.

To facilitate the decision-making process, a more readable decision tree was created, as shown in figure 7. This decision tree can be used as a practical tool for screening tunnels where daytime lighting may be required.

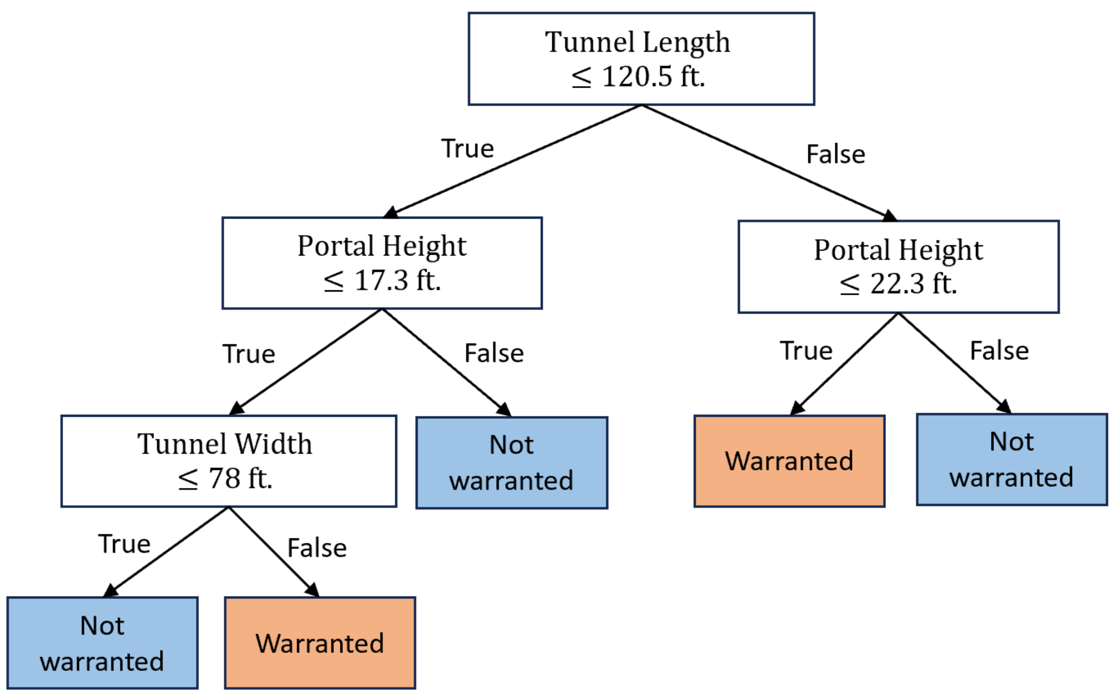


Figure 7. Chart. Decision tree for daytime lighting warrant analysis.

Note: The decision tree in Figures 6 and 7 was estimated based on a small dataset consisting of only span tunnels with limited dimension ranges (tunnel length: 80 ft - 250 ft; tunnel width: 66 ft – 127 ft; portal height: 12.8 ft – 27.1 ft). It does not apply to other tunnel types, such as culvert. Caution should be exercised when extrapolating beyond the dimension ranges of the tunnels in the dataset.

By inspecting figure 6 and figure 7, we see that the tree model places a substantial emphasis on the tunnel dimensionality, including tunnel length, tunnel width, and portal height. These attributes are identified as significant indicators in predicting the existence of an invisible zone within a tunnel. For application, the daytime lighting warrant analysis can be conducted by following through the decision tree from the root to the leaves. If an invisible zone is predicted at the leaf level (the colored rectangles in the decision tree in figure 7), daytime lighting is warranted.

CHAPTER 5. DETERMINATION OF INVISIBLE ZONES FOR LIGHTING INSTALLATION

Task visibility is directly related to task size and corresponds with detection distance (Gibbons et al. 2023), typically from 1 SSD away. Regarding the task size, this study specifically focuses on the visibility of diminutive targets (i.e., 1-ft-square gray boards). Central to the effectiveness of visibility in detecting these small targets on the pavement surface, especially within tunnel environments, is the concept of horizontal illuminance. Horizontal illuminance represents the amount of surface-normal light that is cast onto the pavement surface. It significantly influences how well drivers can perceive these modest objects within a tunnel. Our data analysis has revealed a correlation between the levels of horizontal illuminance and the visibility of the small targets under various field conditions. The results presented in this chapter are based on the horizontal illuminance data.

The classification tree introduced in chapter 4 can be used as a tool for warrant check to identify tunnels where daytime lighting may be necessary. If a tunnel is predicted to have an invisible zone, the next step is to locate the invisible zone for consideration of daytime lighting. First, the team experimented with different function forms to fit the horizontal illuminance data measured in the field. Based on the experiments, the form of power function produced the best data fit and thus was adopted. The process of using power functions for estimating the invisible zone within a tunnel is illustrated in figure 8, where the diffusion of horizontal illuminance from the entrance or exit portals toward the inside of a tunnel is approximated by a power function. The horizontal illuminance threshold value is denoted by the red dashed horizontal line in figure 8. The intersections of the threshold line with the power functions, if present, mark the start and end points of the invisible zone for the tunnel.

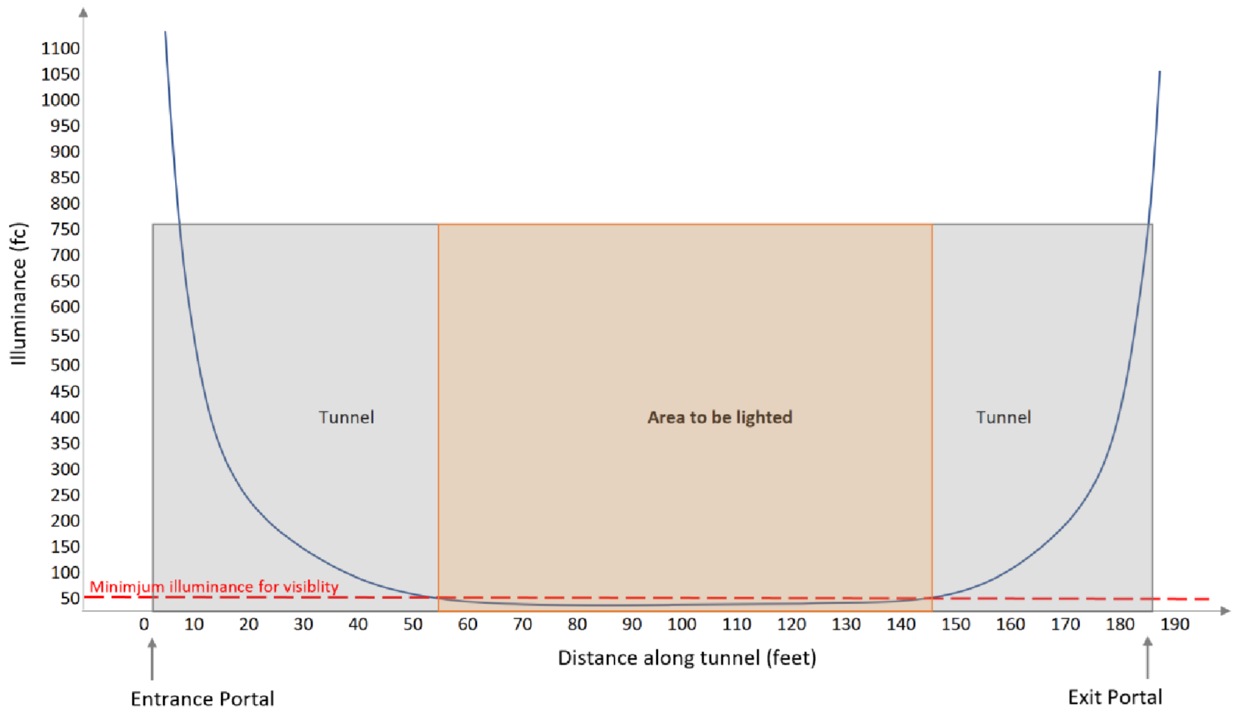


Figure 8. Graph. Determination of the invisible zone based on power function and illuminance threshold.

ESTIMATING CLUSTER-BASED POWER FUNCTIONS FOR DAYLIGHT PENETRATION

First, we fit a power function to the horizontal illuminance data for each individual tunnel, resulting in distinct regression model parameters for each tunnel. To better handle mixed data containing both numeric and categorical features, the factor analysis of mixed data (FAMD) is applied to the joint feature space comprising both tunnel features and regression model parameters for each tunnel. Next, K-means clustering is performed in a low-dimensional space, represented by the first two components of FAMD, leading to three distinct clusters. For better generalization, we fit three power functions, one for each identified cluster, to capture variance in horizontal illuminance across the clusters, which can be considered as a regularization process. For inference with a new tunnel, another classification tree is constructed that takes tunnel features as inputs and predicts the cluster that the new tunnel belongs to. Once a cluster is predicted, the corresponding power function for that cluster is applied with a horizontal illuminance threshold for locating the invisible zone. Each of these steps is described in detail in the following sections.

Power Function Regression

The progression in illuminance within short tunnels can be accurately predicted using a power function in the form of eq. 2:

$$y = f(x) = ax^c \tag{2}$$

where, x is the distance to the tunnel portal and y is the estimated horizontal illuminance value.

For every tunnel, covering both directions (starting from the entrance portal up to the point with the lowest light level), we aim to fit a power function to the horizontal illuminance field measured along that tunnel. Given the large variance in illuminance measurements at the tunnel portals, we discard the illuminance values measured directly at the portals and instead use the illuminance values measured at 10 ft into a tunnel as the reference to normalize the illuminance values farther inside each tunnel. In other words, all the illuminance measurements at 10 ft from the entrance portal and farther inside a tunnel are divided by the illuminance value at 10 ft, resulting in normalized data in the range of 0–1. These normalized data are used to fit power functions, one for each direction of a tunnel. The parameter estimates and goodness of fit (R^2) are summarized in table 1.

Table 1. Parameter estimates of power functions.

Tunnel Name & Direction	Parameter (a)			Parameter (c)			R^2
	Estimate	Lower 95%	Upper 95%	Estimate	Lower 95%	Upper 95%	
Cheshire NB	41.478	32.202	50.753	−1.614	−1.706	−1.523	0.991
Cheshire SB	25.614	18.654	32.574	−1.169	−1.272	−1.067	0.964
GA 70 SW	32.327	28.388	36.267	−1.581	−1.631	−1.531	0.998
GA 70 NE	22.275	12.214	32.335	−1.377	−1.557	−1.198	0.962
GA 139 NB	21.675	16.797	26.553	−1.330	−1.418	−1.241	0.983
GA 139 SB	9.859	6.641	13.078	−1.052	−1.173	−0.931	0.952
GA 280 NB	36.140	26.280	46.000	−1.549	−1.660	−1.439	0.975
GA 280 SB	20.648	9.453	31.844	−1.394	−1.608	−1.180	0.866
I-85 at GA 155 SB	11.508	8.236	14.780	−1.080	−1.185	−0.974	0.962
I-85 at GA 155 NB	13.294	8.330	18.259	−1.165	−1.307	−1.024	0.946
I-85 at GA 20 EB	10.759	5.822	15.696	−1.041	−1.214	−0.869	0.934
I-85 at GA 20 WB	16.923	9.509	24.338	−1.242	−1.413	−1.071	0.960
I-285 at GA 13 SB	57.417	27.645	87.189	−1.777	−1.992	−1.562	0.967
I-285 at GA 13 NB	24.242	19.534	28.950	−1.349	−1.425	−1.272	0.987
I-285 at GA 141 NB	19.850	14.689	25.012	−1.304	−1.405	−1.203	0.975
I-285 at GA 141 SB	17.339	9.536	25.143	−1.303	−1.478	−1.128	0.937
IA 58 NB	17.973	15.472	20.473	−1.255	−1.308	−1.201	0.992
IA 58 SB	11.657	9.751	13.562	−1.060	−1.120	−1.000	0.983
Langford Pkwy NB	45.153	31.883	58.423	−1.264	−1.379	−1.150	0.974
Langford Pkwy SB	18.328	11.337	25.318	−1.283	−1.434	−1.132	0.977
Lindbergh Rd I-85 NB EB	46.309	20.288	72.330	−1.392	−1.617	−1.166	0.961
Lindbergh Rd I-85 SB WB	38.040	18.824	57.255	−1.328	−1.527	−1.129	0.949
Lindbergh Rd I-85 SB EB	21.940	11.393	32.487	−1.180	−1.364	−0.997	0.928
Metropolitan under 1-85	13.823	8.208	19.437	−1.197	−1.355	−1.038	0.968
Metropolitan under Langford EB	3.940	2.708	5.171	−0.620	−0.724	−0.517	0.883
Metropolitan under Langford WB	5.133	3.890	6.375	−0.705	−0.781	−0.630	0.928
Piedmont Rd under Buford NB	59.575	29.589	89.561	−1.497	−1.701	−1.294	0.964
Piedmont Rd under Buford SB	276.066	151.814	400.318	−2.555	−2.748	−2.362	0.998
Piedmont Rd under I-85 SB	6.826	5.627	8.026	−0.603	−0.683	−0.524	0.967
Piedmont Rd under I-85 NB	6.421	1.903	10.939	−0.799	−1.174	−0.423	0.900

Joint Embedding and Clustering

To associate explicit tunnel features with light penetration patterns captured in power function regression parameters, both tunnel features and regression parameters are jointly embedded in a low-dimensional space, followed by clustering analysis to categorize tunnels into distinct classes (clusters). The process is illustrated in figure 9.

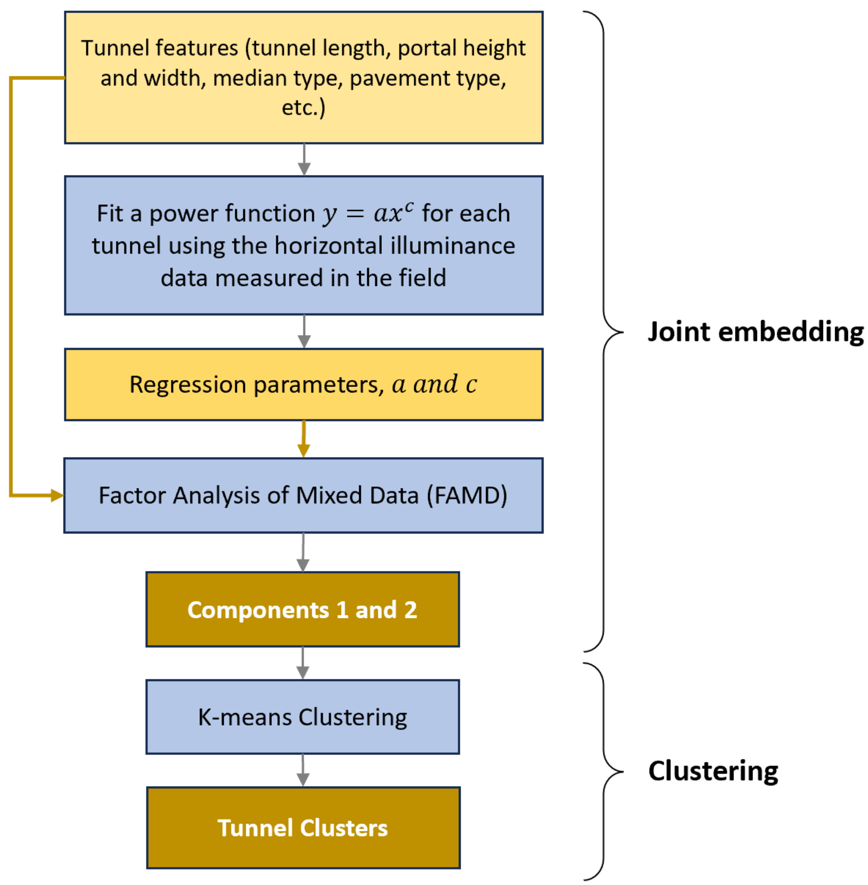


Figure 9. Flowchart. Process of joint embedding and clustering.

For joint embedding, FAMD is employed to reduce the original high-dimensional joint feature space to a low-dimensional feature space. FAMD was selected because the data includes both numeric and categorical features.

We retain the first two components, which captures 77 percent of total data variance in the joint feature space. Then, cluster analysis is performed in this two-dimensional (2-D) feature space to identify cohesive clusters of tunnels that share similar traits and "behavior" in terms of illuminance diffusion along tunnels. For this analysis, the K-means algorithm is applied. It should be noted that each direction of a tunnel was represented as a separate data point in the joint feature space because invisible zones vary by direction.

To determine the optimal number of clusters, the silhouette score is referenced as the evaluation metric, which measures the quality of resultant clusters. A higher silhouette score indicates better clustering. The silhouette scores are plotted against the number of clusters in figure 10, which shows that three clusters achieved the highest silhouette score.

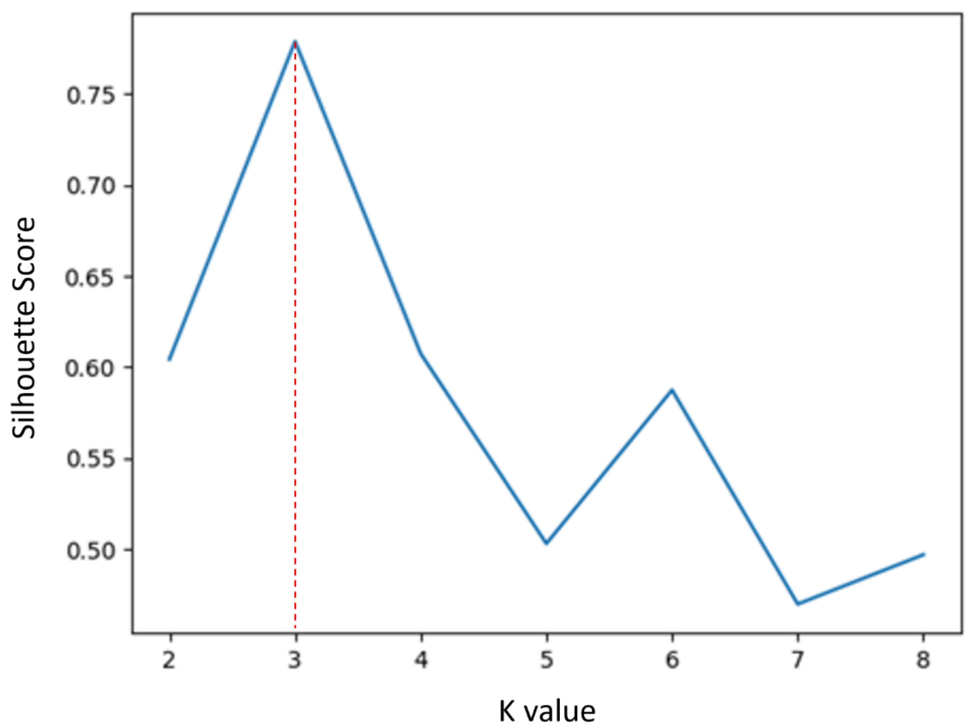


Figure 10. Graph. Selection of the optimal number of clusters.

Figure 11 visualizes the three clusters in the 2-D space formed by the first two components of FAMD.

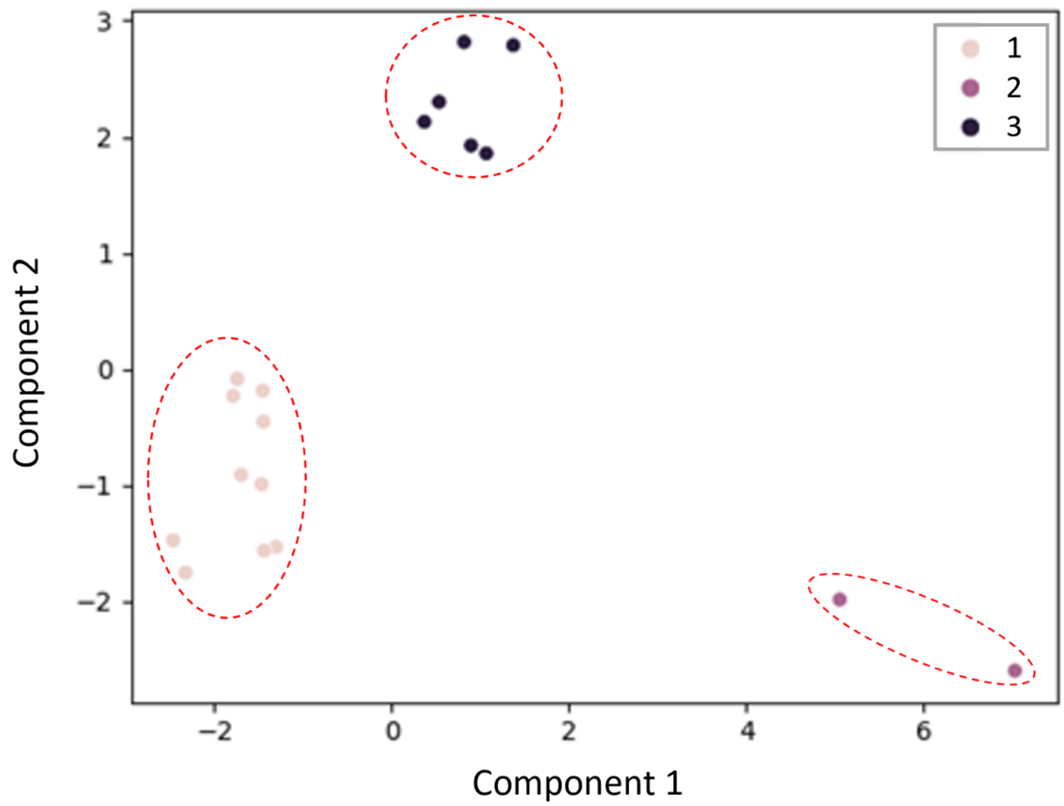


Figure 11. Chart. Visualization of the three clusters.

For evaluation of a new tunnel, a cluster is assigned to the tunnel and the corresponding power function for the cluster is then applied to determine the invisible zone for the tunnel. For cluster assignment, we constructed another classification tree that takes relevant tunnel features to predict which of the three clusters the new tunnel would fit into. The resulting classification tree, depicted in figure 12, succinctly reveals two crucial categorical features: median piers and surface materials. It should be noted that center pier spacing can vary significantly plus there may or may not be a pier wall of varying height. The presence of median piers largely impacts the penetration of light with in the tunnel, while the choice of surface materials directly governs the light reflection characteristics. For implementation, a more readable tree is shown in figure 13.

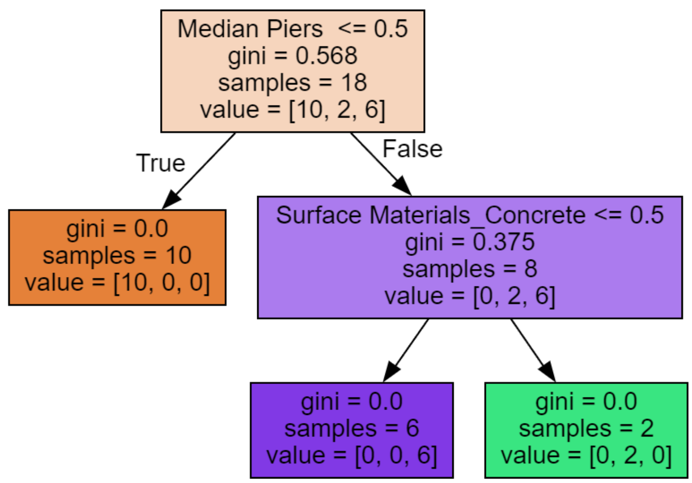


Figure 12. Chart. Construction of classification tree for tunnel categorization.

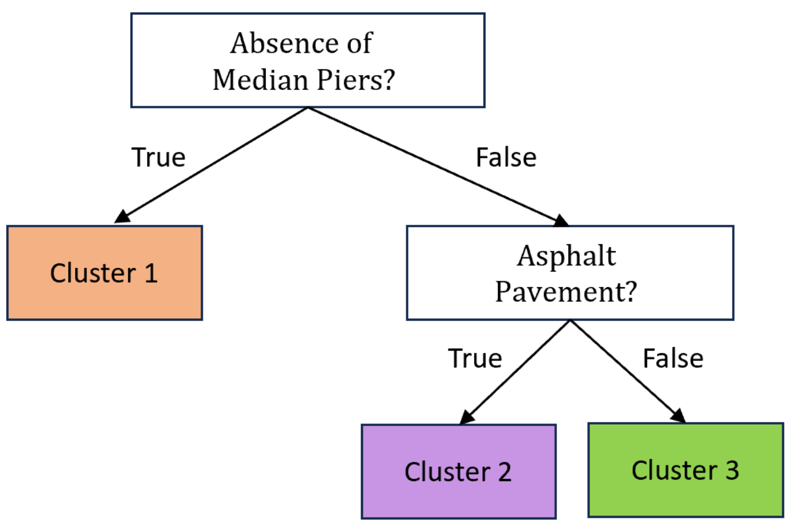


Figure 13. Chart. Decision tree for tunnel categorization.

Power Function for Each Tunnel Cluster

To improve generalization, the team fits a new power function for each of the three tunnel clusters identified in the previous section. The new parameters are summarized in table 2, and the corresponding power functions are plotted in figure 14.

Table 2. Summary of the power functions for the three tunnel clusters.

Cluster ID	Cluster Size	R^2	Parameter	
			a	*c*
1	10	0.811	269.706	−1.954
2	6	0.840	71.756	−1.708
3	2	0.838	17.154	−1.493

Note: the cluster analysis is based on directional data from the nine span tunnels, which exhibit invisible zones based on the field visibility observations.

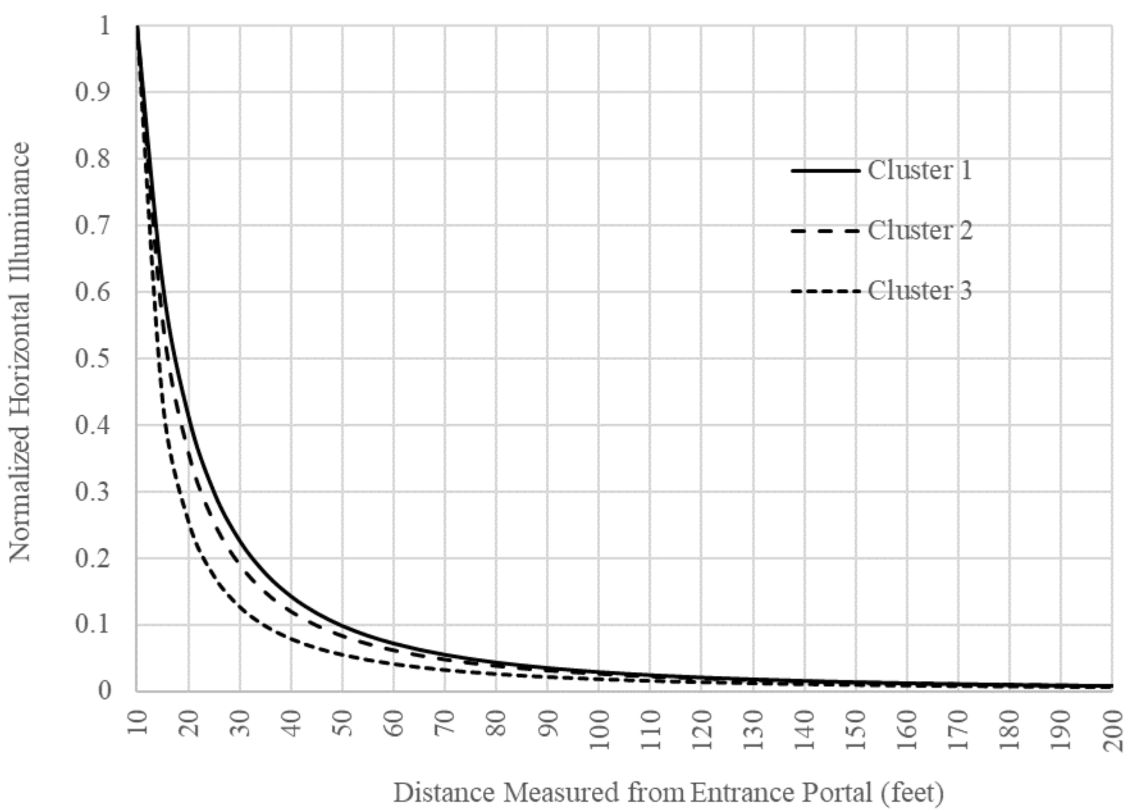


Figure 14. Graph. Plot of power functions by clusters.

DETERMINING ILLUMINANCE THRESHOLD FOR INVISIBILITY ASSESSMENT

As mentioned, horizontal illuminance is used in reference to visibility for two reasons: (1) it reflects the actual visibility of small objects on the pavement surface inside a tunnel, and (2) it correlates well with field observations of invisible zones. In this section, the team aims to establish a horizontal illuminance threshold for determining invisible zones in short tunnels by matching the observed invisible zones with those derived from (1) cluster-based power functions, and (2) 2-D simulations.

Matching Invisible Zone by Cluster-based Power Functions

By referencing the estimated power function for each cluster, the optimal horizontal illuminance threshold value is found by minimizing the total absolute error that is computed as the summation of absolute differences (errors) between the estimated and the observed invisible zones of the tunnels.

Let $y = f_j(x)$ be the power function for cluster j. Given an arbitrary horizontal illuminance threshold value θ, the start and end points of the invisible zone for tunnel i in cluster j ($x_{j,i,s}$, $x_{j,i,e}$) can be estimated by the inverse of the power function, i.e., $\hat{x}_{j,i,s} = f_{j,i,s}^{-1}(y = \theta)$ and $\hat{x}_{j,i,e} = f_{j,i,e}^{-1}$ $(y = \theta)$.

In figure 15, the blue rectangle denotes the observed invisible zone in the field and the orange rectangle indicates the estimated invisible zone by the model. The errors are measured by the offsets between the two rectangles.

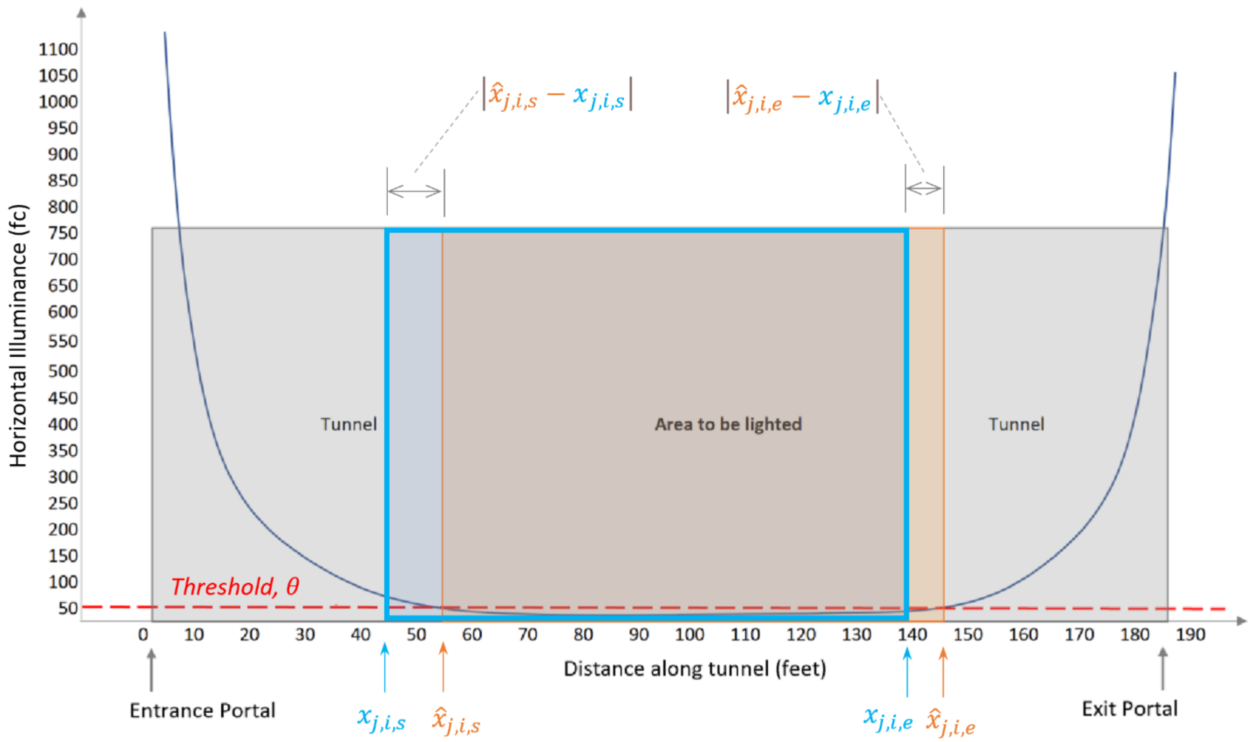


Figure 15. Graph. Illustration of error computation for invisible zone matching.

The optimal threshold θ^* is found by minimizing the total absolute errors, as expressed in eq. 3:

$$\theta^* = \underset{\theta}{\operatorname{argmin}} \sum_j \sum_{i \in j} \left(\left| f_{j,i,s}^{-1}(y = \theta) - x_{j,i,s} \right| + \left| f_{j,i,e}^{-1}(y = \theta) - x_{j,i,e} \right| \right) \tag{3}$$

Where, $x_{j,i,s}$ and $x_{j,i,e}$ are observed start and end points of an invisible zone for tunnel i in cluster j.

The solution of the optimization problem leads to a horizontal illuminance threshold of 46 fc.

Matching Invisible Zones by 2-D Simulations

In addition to the power function regression approach, we simulate the illuminance diffusion in these tunnels using the Lambert cosine law of illumination (eq. 4):

$$E = \frac{I cos(\alpha)}{r^2} \tag{4}$$

where, E indicates horizontal illuminance (fc), I indicates light intensity (lumens), α indicates surface normal light angle, and r indicates distance (ft). The simulation input includes geometrical features of a tunnel, such as height and length, and the illuminance at the portals of the tunnel. The 2-D simulation is applied to simulate horizontal illuminance for all tunnels. Figure 16 shows an example plot, where illuminance distribution throughout the tunnel is depicted by color.

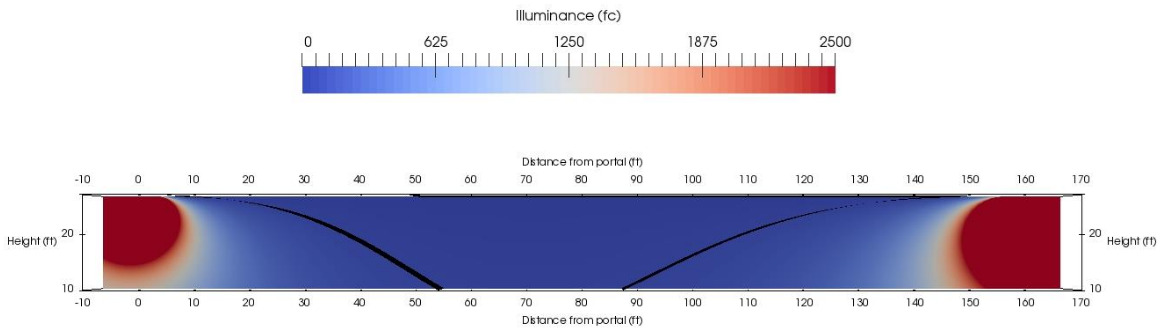


Figure 16. Illustration. Example of illuminance distribution with 46 fc contour (tunnel: GA 70 under I-20).

In the same plot, contour lines can be displayed to show the bounded area by any illuminance value. For example, in figure 16, the contour of illuminance of 46 fc is shown. The inner area bounded by the contour lines is the region where the illuminance is lower than 46 fc. It is assumed that the area with low horizontal illuminance would be darker and therefore is more likely to contain the invisible zone. This was confirmed by field observation of invisible zones. With this assumption, the bounds of the contour lines at the pavement level were extracted. Absolute errors between the simulated and observed invisible zones were computed and are included in Appendix A. This approach is similar to the approach outlined in Matching Invisible Zone By Cluster-Based Power Functions. The difference is that the regression models are estimated from detailed field illuminance measurements for the identified clusters of tunnels, whereas the simulation adheres to the Lamb ert cosine law of illumination. To further illustrate this process, an example of error calculation is shown in figure 17.

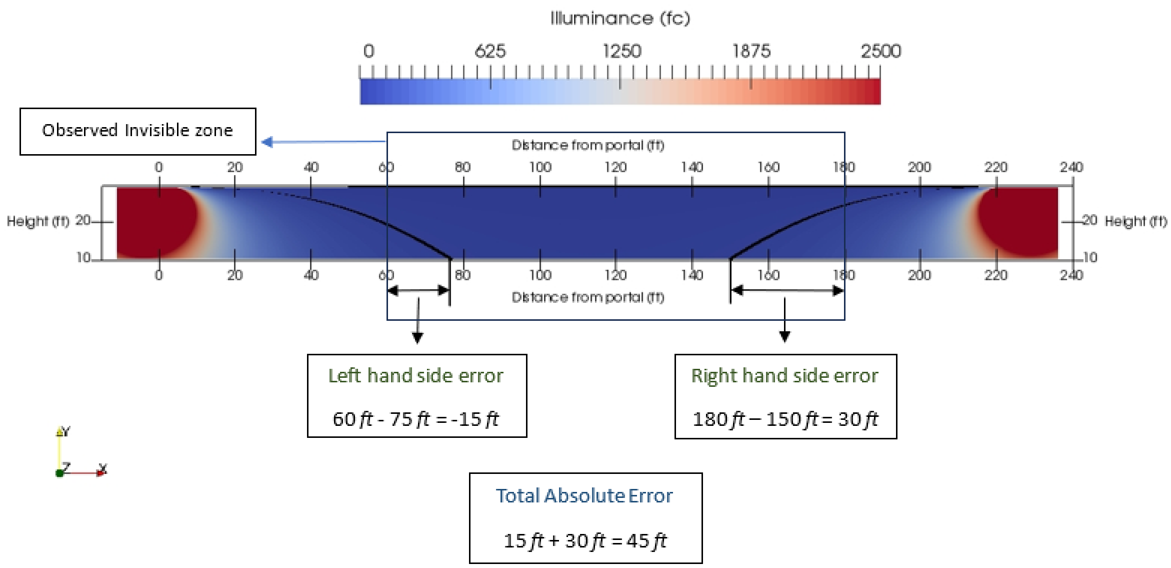


Figure 17. Diagram. Example of absolute error calculation from 2-D simulation.

The computed absolute errors were plotted to graphically discern the critical value of illuminance. The upper, average, and lower bounds of the absolute errors versus horizontal illuminance threshold values were shown in figure 18. The plot indicates that the horizontal illuminance value that produces the least variation in absolute error lies between 30 and 50 fc. This suggests that the horizontal illuminance value in this range tends to produce regions that best represent the field-observed invisible zones. Notably, this range contains the optimal horizontal illuminance threshold value (46 fc) obtained from the optimization method described previously.

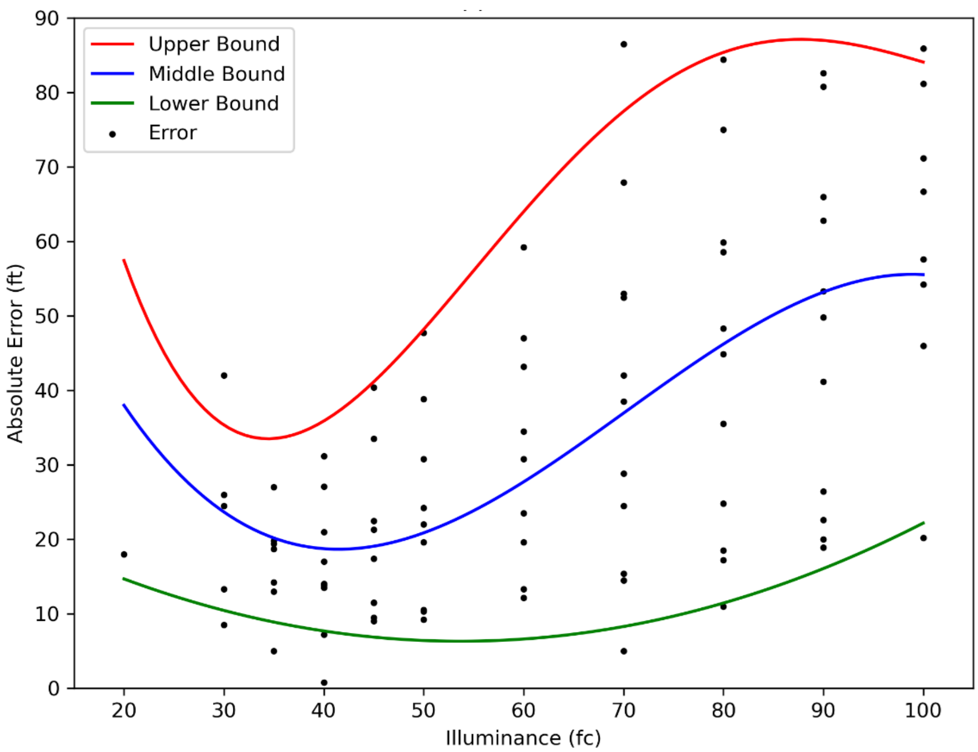


Figure 18. Graph. Absolute error versus horizontal illuminance threshold.

It should be noted that the large variation of the errors is due to the simplicity of the 2D model, which disregards many influential factors, such as tunnel width, presence of a median, pavement type, etc. At this stage, the 2-D simulation model is utilized as a tool to visualize the light distribution within a tunnel and to cross-check the critical threshold of horizontal illuminance that correlates with the invisible zones of all tunnels.

CHAPTER 6. APPLICATION DEMONSTRATION

To facilitate the practical implementation of the methods developed in this study, a decision flowchart is constructed and presented in figure 19. To exemplify the application process, a hypothetical example has been employed, providing a step-by-step demonstration in the following subsections on Lighting Warrant Analysis and Invisible Zone Determination.

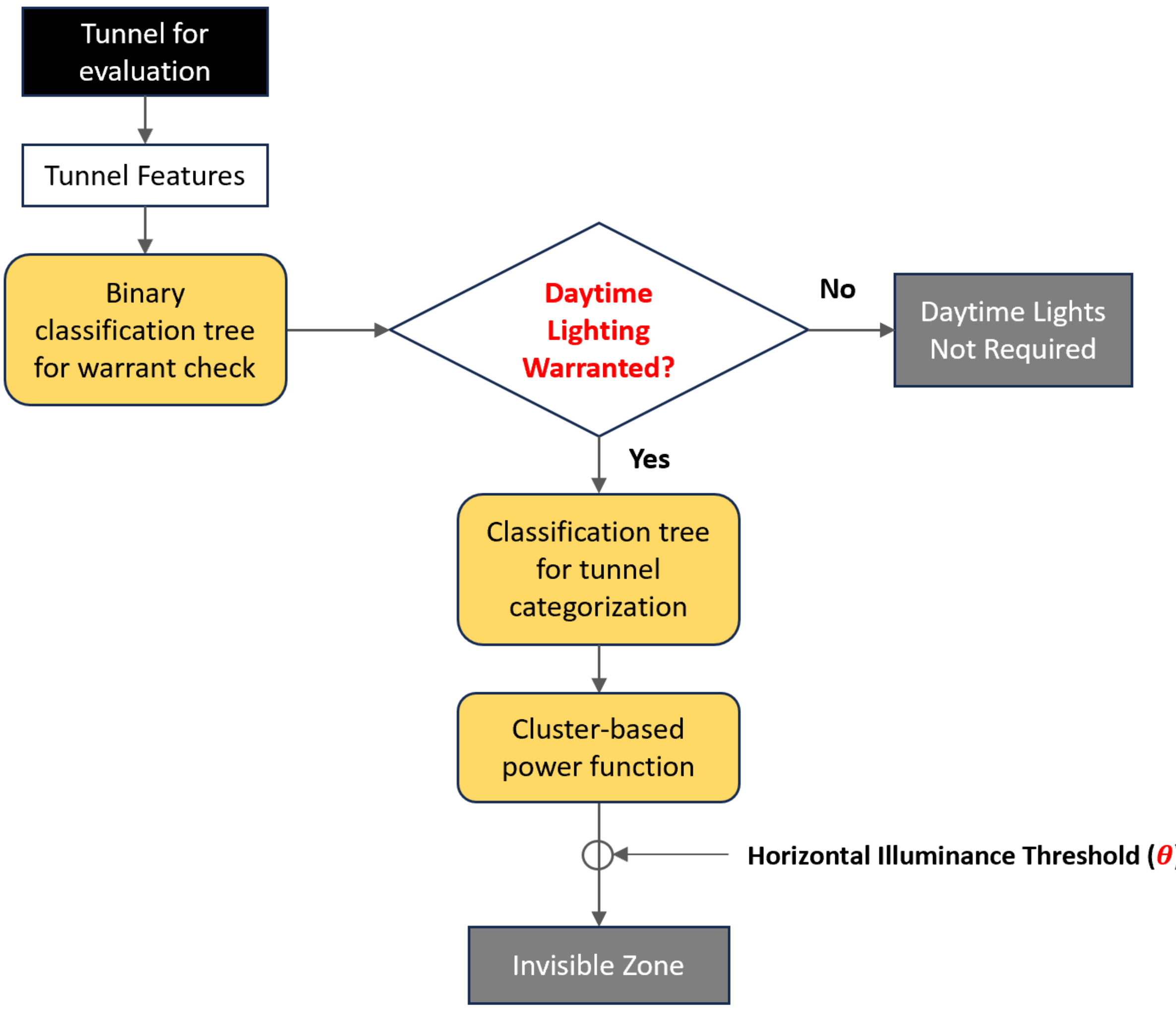


Figure 19. Flowchart. Decision flowchart.

LIGHTING WARRANT ANALYSIS

To demonstrate the daytime lighting warrant analysis, a hypothetical tunnel is used with the tunnel features and horizontal illuminance values measured at 10 ft into the entrance portal and 10 ft before the exit portal (table 3).

Table 3. Hypothetical tunnel features and horizontal illuminance.

Tunnel Feature	**Value**
Tunnel length	115 ft
Portal height	16.5 ft
Tunnel width	80 ft
Median piers	Yes
Pavement type	Asphalt
Horizontal Illuminance	**Value**
10 ft into the entrance portal	500 fc
10 ft before the exit portal	500 fc

By following the previously established binary classification tree as indicated by the decision path in red lines in figure 20, daytime lighting is warranted for this tunnel.

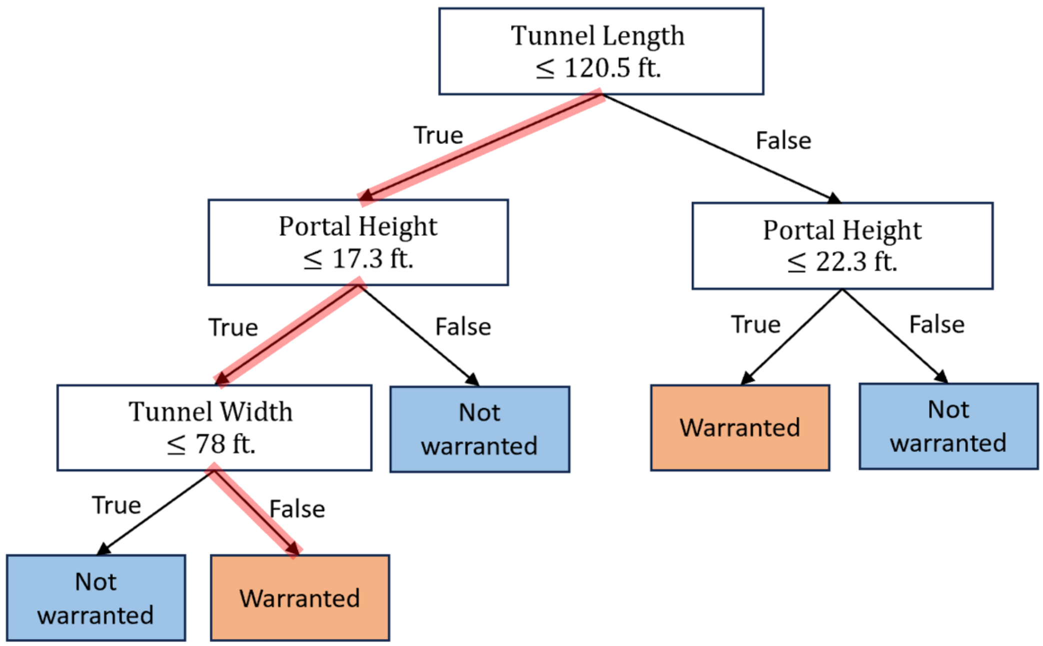


Figure 20. Chart. Application of decision tree for daytime lighting warrant analysis.

INVISIBLE ZONE DETERMINATION

First, the cluster that the tunnel belongs to is determined by applying the classification tree for tunnel categories in figure 13. Based on the tunnel features, we can determine that this tunnel falls into cluster 2, as depicted in figure 21 by following the decision path in red. Then the previously established horizontal illuminance threshold of 46 fc is applied with the power function for cluster 2. The process is depicted in figure 22. This results in an invisible zone from 47 ft to 68 ft measured from the entrance portal. It should be noted that the standardized power functions in figure 14 were estimated based on the illuminance values normalized to the value of 1.0 at the portal of each tunnel (precisely 10 ft from the portal as the reference point). The illuminance values further inside the tunnel were scaled down accordingly by referencing the value at the 10 ft. In other words, all illuminance values beyond 10 feet from the portal were divided by the illuminance value at 10 feet location. Consequently, when applying the power functions (figure 14), the outputs need to be

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caled up by multiplying the actual illuminance values at 10 feet into the entrance portal and at 10 feet before the exit portal to obtain predicted illuminance values.

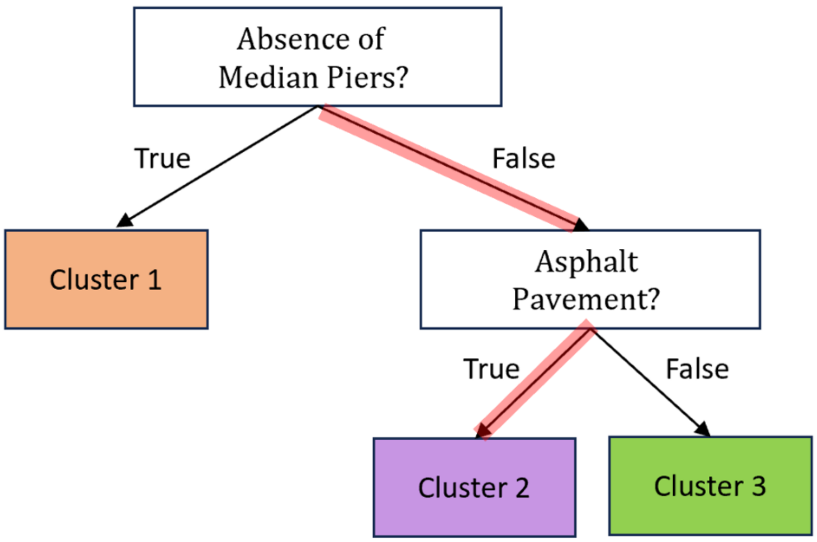

Figure 21. Chart. Application of the classification tree for tunnel cluster categorization.

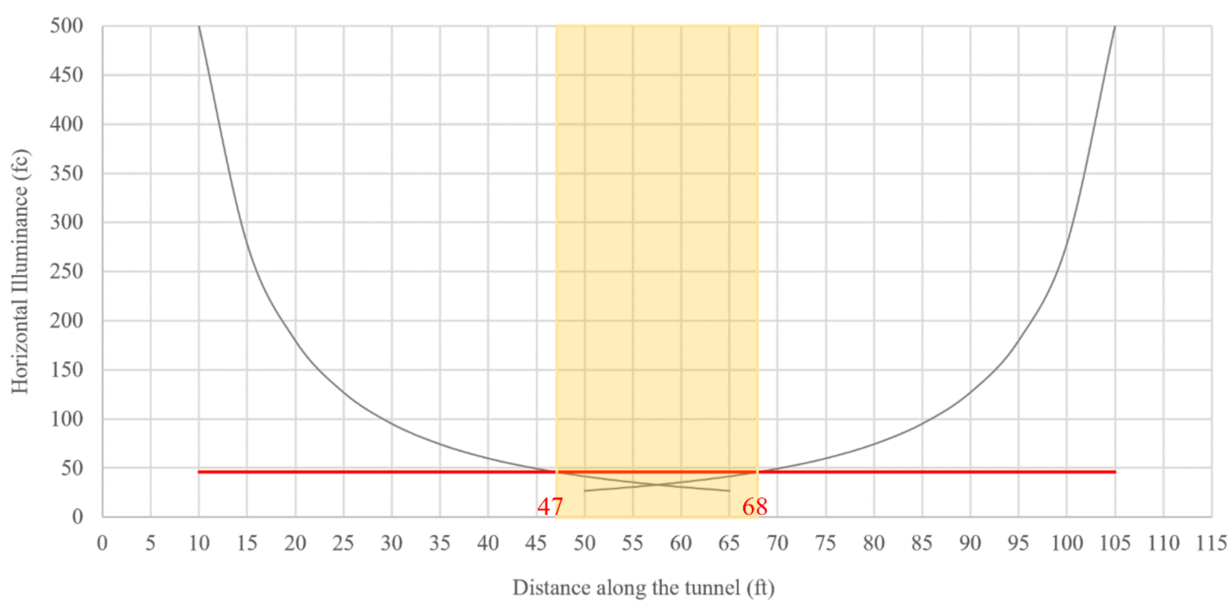

Figure 22. Graph. Application of cluster-based power regression model for locating the invisible zone.

CHAPTER 7. CONCLUSIONS AND RECOMMENDATIONS

In conclusion, this study investigates a data-driven approach that leverages modern machine learning methods and algorithms for evaluating the necessity and extent of daytime lighting in short tunnels. By harnessing the field-measured luminance and illuminance data as well as visibility observations for short tunnels, a binary classification tree (figure 7) is developed to aid with daytime lighting warrant analysis. Depending on the outcome of the warrant analysis, a further evaluation of the area to light is undertaken if daytime lighting is warranted. The form of power function was selected for light penetration modeling due to its best fit to the data. First, a unique power function was fitted to the illuminance data of each tunnel to capture its distinct light penetration pattern. To associate the tunnel features with light penetration patterns, a 2-D joint embedding space is constructed, where distinct clusters of tunnels are identified. Subsequently, a power function regression model is developed for each cluster of tunnels. This clustering serves as a regularization process to mitigate the risk of overfitting and improve generalization. The cluster-based regression models were finally applied with a horizontal illuminance threshold to determine invisible zones for lighting consideration. The optimal horizontal illuminance threshold value of 46 fc was determined by minimizing the matching errors between the predicted invisible zones and those observed in the field. This threshold quantifies the minimum level of light required to alleviate visibility issues for approaching drivers.

Regardless of the practicality of the procedure developed from this study, the research team duly acknowledges the study's inherent limitations. Notably, all tunnels in the dataset for this study are less than 250 ft. The four culvert tunnels in the dataset have ambiguous feature annotations in contrast with span tunnels; thus, they were excluded as part of the data curation process. Considering the data-centric nature of this study, the limited and imbalanced tunnel data can potentially result in biased models that struggle to generalize effectively to new tunnel scenarios. Additionally, as highlighted in the recently published *Lighting Handbook* (FHWA 2023), the drivers' view of the exit portal is an important element for determining if and how to light short tunnels. Unfortunately, this aspect has not been explicitly considered in the current models. As such, solely relying on a threshold of horizontal illuminance to determine an invisible zone may not be adequate for short tunnels, where the visibility of small objects to drivers is also influenced by the extent of the exit portal that appears in the approaching drivers' view. In other words, the high vertical illuminance reflected in the backdrop of the exit portal in the drivers' view effectually imposes a "black frame" (see figure 23; as opposed to a "black hole" in longer tunnels) that would significantly affect the visibility of small objects within the black frame. Furthermore, the research team hypothesizes that especially in areas where horizontal illuminance is low, the role of vertical illuminance assumes greater significance in either facilitating illumination of target objects or exacerbating the pronounced illuminance contrast in the background (i.e., the black frame effect), which can impede human vision. An in-depth examination of these pivotal factors is essential for more precise demarcation of zones for supplemental lighting installation.

Figure 23. Illustration. Black frame due to the visibility of the exit portal in the approaching drivers' view.

In response to these challenges, a subsequent phase of study is proposed to adopt a “physics-guided machine learning” approach. This novel approach involves the infusion of physics principles into the ML process, thereby augmenting model reliability and interpretability. To address the need for a comprehensive dataset, additional tunnel data will be collected to supplement the dataset of the current study. Moreover, the team aims to leverage AGi32 software to simulate corner cases, ensuring that the models are robust and capable of handling various scenarios.

APPENDIX A:
ATTRIBUTES OF FIELD MEASURED TUNNELS

	Tunnel Type	Surface Materials	Outside Structure	Outside Paved Slope	Median Type	Portal Height (ft)	Tunnel Length (ft)	Tunnel Width (ft)	MPH
Cheshire NB	Culvert	Asphalt	Piers & Walls	No	None	15.9	189	108.8	35
Cheshire SB	Culvert	Asphalt	Piers & Walls	No	None	17.53	189	111.8	35
GA 70 at I-20 NE	Span	Asphalt	Piers	Yes	Piers	17.38	160	106	35
GA 70 at I-20 SW	Span	Asphalt	Piers	Yes	Piers	16.75	160	106	35
GA 139 at I-20 NB	Span	Asphalt	Piers	Yes	None	17.6	160	87	35
GA 139 at I-20 SB	Span	Asphalt	Piers	Yes	None	16.81	160	87	35
GA 280 at I-20 NB	Span	Asphalt	Piers	Yes	None	18.52	225	87	35
GA 280 at I-20 SB	Span	Asphalt	Piers	Yes	None	15.9	225	87	35
GA 316 at GA 53 NW	Culvert	Concrete	Walls	No	None	19.5	150	114	55
GA 316 at GA 53 SE	Culvert	Concrete	Walls	No	None	21	150	114	55
I-85 at GA 155 NB	Span	Asphalt	Piers	Yes	None	18.75	175	120	40
I-85 at GA 155 SB	Span	Asphalt	Piers	Yes	None	20.4	175	120	40
I-85 at GA 20 WB	Span	Asphalt	Piers	Yes	Piers	23.29	127	125.5	45
I-85 at GA 20 EB	Span	Asphalt	Piers	Yes	Piers	24.21	127	125.5	45
I-285 at GA 13 SB	Span	Asphalt	Piers	Yes	Piers	16.85	200	127	35
I-285 at GA 13 NB	Span	Asphalt	Piers	Yes	Piers	17.21	200	127	35
I-285 at GA 141 NB	Span	Asphalt	Piers	Yes	Piers	18.02	227	99.2	45
I-285 at GA 141 SB	Span	Asphalt	Piers	Yes	Piers	20.01	227	99.2	45
IA 58 NB	Culvert	Concrete	Walls	No	None	17.83	225	99	55
IA 58 SB	Culvert	Concrete	Walls	No	None	19	225	99	55
Langford Pkwy NB	Culvert	Concrete	Walls	No	Walls	20.46	149.75	98.6	55
Langford Pkwy SB	Culvert	Concrete	Walls	No	Walls	18.5	149.75	98.6	55
Lindbergh Rd I-85 NB WB	Span	Asphalt	Piers	Yes	None	17.7	85	72.5	35
Lindbergh Rd I-85 NB EB	Span	Asphalt	Piers	Yes	None	16.95	78	72.5	35
Lindbergh Rd I-85 SB WB	Span	Asphalt	Piers	Yes	None	17.75	121	83.5	35

Lindbergh Rd I-85 SB EB	Span	Asphalt	Piers	Yes	None	17.17	109	83.5	35
Metropolitan Pkwy under I-85 WB	Span	Asphalt	Piers	Yes	None	16.96	117	72	55
Metropolitan Pkwy under I-85 EB	Span	Asphalt	Piers	Yes	None	17.07	117	72	55
Metropolitan Pkwy under Langford WB	Span	Asphalt	Piers	Yes	None	21.25	167.75	78.5	35
Metropolitan Pkwy under Langford EB	Span	Asphalt	Piers	Yes	None	21.33	139.83	78.5	35
Piedmont Rd under Buford NB	Span	Concrete	Piers	Yes	Piers	17.43	121	89	35
Piedmont Rd under Buford SB	Span	Concrete	Piers	Yes	Piers	18.15	121	89	35
Piedmont Rd under I-85 NB	Span	Concrete	Piers	No	None	24.93	205	85	35
Piedmont Rd under I-85 SB	Span	Concrete	Piers	No	None	27.11	205	85	35
Racine 7-9	Span	Concrete	Walls	No	Piers	12.83	200	66	30
Racine 4-6	Span	Concrete	Walls	No	Piers	12.83	200	66	30

APPENDIX B:
ABSOLUTE ERROR VERSUS ILLUMINANCE THRESHOLD (2-D SIMULATION)

Tunnel Name	**Illuminance (fc)**	**Abs Error (ft)**
Lindbergh under I-85	70	5
	80	11
	90	20
Piedmont Under Buford	30	26
	35	19.8
	40	21
	45	21.3
	50	22
	60	23.5
	70	24.5
	80	24.8
	90	26.4
GA 141 under I-285	30	13.3
	35	19.4
	40	31.2
	45	40.4
	50	47.7
	60	59.2
	70	67.9
	80	75
	90	80.8
	100	85.9
GA 280 at I-20	35	14.2
	40	13.8
	45	22.5
	50	30.8
	60	43.2
	70	52.5
	80	59.9
	90	66
	100	71.2

Tunnel Name	Illuminance (fc)	Abs Error (ft)
GA 53 under GA 316	70	86.5
	80	84.4
	90	82.6
	100	81.2
GA 155 under I-85	35	13
	40	13.5
	45	17.4
	50	24.2
	60	34.5
	70	42
	80	48.3
	90	53.3
	100	57.6
Langford under RR Tracks at Mai	20	18
	30	24.5
	35	5
	40	7.2
	45	9
	50	10.5
	60	13.3
	70	15.4
	80	17.2
	90	18.9
	100	20.2
GA 70 and I-20 SW	40	0.8
	45	11.5
	50	19.6
	60	30.8
	70	38.5
	80	44.9
	90	49.8
	100	54.2

Tunnel Name	Illuminance (fc)	Abs Error (ft)
Metropolitan Under Langford	30	42
	35	27
	40	17
	45	9.5
	50	9.2
	60	12.15
	70	14.5
	80	18.5
	90	22.6
Cheshire bridge under I-85	40	14
	45	11.5
	50	10.3
	60	19.6
	70	28.8
	80	35.5
	90	41.2
	100	46
GA 139 at I-20	30	8.5
	35	18.7
	40	27.1
	45	33.5
	50	38.8
	60	47
	70	53
	80	58.6
	90	62.8
	100	66.7

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REFERENCES

American Association of State Highway and Transportation Officials (AASHTO). (2018). "Tunnels and Underpasses." *Roadway Lighting Design Guide*, Chapter 4, U.S. Department of Transportation, Federal Highway Administration, Washington, DC, pp. 38–44.

Anundsen, F.H. and Engebretsen A. (2009). *Studies on Norwegian Road Tunnels II: An Analysis on Traffic Accidents in Road Tunnels 2001–2006*. Road and Traffic Department, Traffic Safety Section, TS4-2009, Statens Vegvesen, Oslo, Norway. Available online: http://hdl.handle.net/11250/192582.

Bassan S. (2016). "Overview of Traffic Safety Aspects and Design in Road Tunnels." *IATSS Research*, *40*(1), pp. 35–46. Available online: https://doi.org/10.1016/j.iatssr.2016.02.002.

Ceriotti, M., Corrà, M., D'Orazio, L., Corin, R.D., Facchin, D., Guna, S.T., Jesi, G.P., Lo Cigno, R.A., Mottola, L., Murphy, A.L., et al. (2011). "Is There Light at the Ends of the Tunnel? Wireless Sensor Networks for Adaptive Lighting in Road Tunnels." In *Proceedings of the 10th International Conference on Information Processing in Sensor Networks*, April 12–14, Chicago, IL, pp. 187–198.

Colorado Department of Transportation (CDOT). (2020). "Tunnels." *Lighting Design Guidelines*, Chapter 2.2.5, CDOT, Denver, CO, pp. 13–15. Available online: https://www.codot.gov/safety/traffic-safety/assets/documents/cdot-lighting-design-guideline-2020.pdf.

Gibbons, R., McLean, D., Lutkevich, P., Bhagavathula, R., and Keith, D. (2023). *2023 FHWA Lighting Handbook*. Report No. FHWA-SA-23-004, Virginia Tech Transportation Institute, Blacksburg, VA. Available online: https://highways.dot.gov/sites/fhwa.dot.gov/files/2023-05/FHWA-Lighting-Handbook_0.pdf.

Hargroves, R.A. and Lamb, P.J. (1989). "New Recommendations for Tunnel Lighting." *Lighting Journal*, *54*(2).

Hirakawa, S., Karasawa, Y., Funaki, T., and Yoshida, Y. (2014). "Evaluation Index of Visibility in Tunnel Lighting." *Journal of Light & Visual Environment*, *38*, pp. 117–127. Available online: https://doi.org/10.2150/jlve.IEIJ130000529.

Hu, J., Gao, X., Wang, R., Xu, P., and Miao, G. (2019). "Safety Evaluation Index on Daytime Lighting of Tunnel Entrances." *Advances in Mechanical Engineering*, *11*(5), 1687814019854568. Available online: https://doi.org/10.1177/1687814019854568.

Illuminating Engineering Society (IES). (2021). *Lighting Roadway and Parking Facilities*. Recommended Practice, ANSI/IES RP-8-22, New York.

Nederlandse Stichting voor Verlichtingskunde (NSVV). (1963). "Aanbevelingen voor tunnelverlichting." *Electro-Techniek*, *41*(2), pp. 23–53.

Ohio Department of Transportation (ODOT). (2023). “Warrant for Daytime Tunnel Lighting.” *Traffic Engineering Manual* (TEM), Chapter 1103.6.9.3, ODOT Office of Roadway Engineering, Design Standards Section, Columbus, OH. Available online: https://www.transportation.ohio.gov/working/engineering/roadway/manuals-standards/tem/11/11.

Qin, L., Dong, L., Xu, W., Zhang, L., Yan, Q., and Chen, X. (2017). “A ‘Vehicle In, Light Brightens; Vehicle Out, Light Darkens’ Energy-saving Control System of Highway Tunnel Lighting.” *Tunnelling and Underground Space Technology*, *66*, pp. 147–156. Available online: https://doi.org/10.1016/J.TUST.2017.04.014.

Wang, Y., Cui, Y., Chen, F., and Ren, R. (2020). “An ‘Illumination Moving with the Vehicle’ Intelligent Control System of Road Tunnel Lighting.” *Sustainability*, *12*(18), 7314. Available online: https://doi.org/10.3390/su12187314.

Zhao, J., Feng, Y., and Yang, C. (2021). “Intelligent Control and Energy Saving Evaluation of Highway Tunnel Lighting: Based on Three-dimensional Simulation and Long Short-term Memory Optimization Algorithm.” *Tunnelling and Underground Space Technology*, *109*, 103768. Available online: https://doi.org/10.1016/j.tust.2020.103768.