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ANALYSIS AND EVALUATION OF SHORT CITY TUNNEL LIGHTING SOLUTIONS

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Abstract. The study focused on the lighting in road tunnels within the city of Vilnius. The condition of the lighting was assessed both visually and through measurements of road surface illumination (brightness). High-quality lighting in road tunnels is crucial for ensuring safe and optimal conditions for car travel. Well-designed lighting reduces stress, enhances information visibility for drivers, ensures uniform visibility throughout the tunnel, and promotes efficient energy use. After analysing the data, the required road surface luminance was calculated following the technical regulations applicable to road tunnel lighting design in other countries. The results suggest a need to update the lighting in existing road tunnels by adopting new types of lamps, adjusting their arrangement, and enhancing the physical characteristics of the tunnels.

Keywords: lighting zones, lighting requirements, principles of lighting, road tunnel, road surface luminance, tunnel lighting.

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Introduction

Objects in the dark become noticeable only when illuminated by a light source. Therefore, lighting is essential not only for accentuating architectural elements but also for fulfilling practical human needs such as safety, orientation, and information signage. The road and traffic surfaces must reflect light effectively to ensure safe and comfortable night-time driving conditions. Well-lit road surfaces make objects clearly visible to drivers, contributing to safer travel. The road surface luminance depends on the amount of light falling on it and the luminance properties of the road surface (Lunkevičiūtė et al., 2023). Luminance is reflected light, when the incident light flux is reflected from the surface of the road pavement. Luminance can be diffuse and specular, with specular luminance matching the angle of incidence, and diffuse luminance occurs when a beam of parallel rays reflects off an uneven surface and spreads in different directions.

Lighting technology is advancing rapidly, with the advent of Light Emitting Diode (LED) technology akin to the invention of the first light bulb. LEDs are semiconductor devices that convert electric current directly into light, boasting longevity and compactness. LEDs are small light sources that, unlike conventional incandescent bulbs, do not have a filler that can burn out. The LED consists of several layers of semiconductor, and the light is generated in its active layer. Lithuania's road and street lighting network is swiftly adopting LED technology due to its economic advantages, double power efficiency compared to sodium lamps, durability, automatic lighting control, and compact design. LED-type lights with asymmetric optical systems (counter-beam lights) enhance object-background contrast on roadways vs. symmetrical light distribution. These types of illuminators are most effective when providing the high or increased tunnel lighting required at the tunnel entrances and transition areas with minimal installation (Pachamanov & Pachamanova, 2008; Yoomak at al., 2017; Liang et al., 2020).

Road tunnel lighting significantly impacts frequent travellers, as it operates around the clock within tunnels. The quality of lighting in tunnels affects how drivers perceive information and react to road conditions, especially in the dark, with the aim of preventing accidents.

When evaluating tunnel lighting, parameters like tunnel dimensions (length, width, and height), reflective materials, and lighting technology should be taken into account. Therefore, the analysis of road tunnel lighting is a relevant and crucial subject. Determining how lighting conditions change in potential tunnel areas and finding solutions for improved visibility can lead to reduced driver stress, enhanced traffic conditions, and reduced energy costs (Zhao at al., 2021).

Surprisingly, there are few published scientific articles in Lithuania and other Baltic countries related to the evaluation of road tunnel lighting and their importance in everyday life. A 2021 article on smart city lighting addressed the issue of excessive light, which can raise glare levels and energy consumption unnecessarily (Avotins et al., 2021). It found that the LED ballast and control node accuracy can be improved with a "dimming profile" algorithm, potentially saving 8.0–10.0% of energy.

Brightness – describes the intensity of light emitted by a unit of surface area (m^2) perpendicular to the surface.

Luminosity – the density of light flux emitted by the surface.

Illumination (E, lx) – the light flux falling on a surface element at some point of the surface, divided by the area of that element. Illumination depends on the strength of the light source and its distance to the surface. If the distance of the lamps from the illuminated surface is doubled, the illumination decreases four times, requiring a four times stronger light source. On the other hand, the greater the distance to the illuminated surface, the more evenly the light is distributed on that surface.

1. Methods for determining tunnel brightness

Given the rapid evolution of lighting technologies, Lithuania's current regulations for ensuring quality tunnel lighting have become outdated, no longer valid, and await renewal due to the limited experience and structures available in Lithuania.

The Lithuanian standard LST EN 13201-2:2016, titled "Road Lighting. Part 2. Requirements for Operational Characteristics", defines road and street lighting classes and measurement units that determine the necessary light brightness during day and night. Consequently, methods for road tunnel lighting are being studied by adopting best practices from other countries.

The division of road tunnels into lighting zones is described in scientific articles and normative documents of other countries (Liu, 2005; Rands, 2016; Tunnel lighting, 2015; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

Luminance in the selected object is measured by Lumicam 1300 Mono camera, HIOKI FT 3425 Lux meter and LMT L 1003 Luminance meter.

In order to measure the amount of luminance in the selected object, two measuring devices can be used, namely, Lumicam 1300 Mono camera, HIOKI FT 3425 Lux meter and LMT L 1003 Luminance meter.

Lumicam 1300 Mono camera measures the luminance in outdoor conditions at a selected object. The camera photometer and colorimeter record the complex luminance and colour distribution of the screen and electronic panel graphics in the selected measurement object within a few seconds. The size of the measured object can be up to 60.0 m long and the entire width of the roadway. Measurements are made from a height of 1.20–1.50 m. The received data are processed by the device software itself. Units of measurement – candelas (cd).

HIOKI FT 3425 Lux meter is a light flux meter that is mainly used to measure the surface reflectance of sidewalks and non-carriageways. Measurements are made at a height of about 20.0 cm. Device measures objects of about 30.0 m long (usually between two light poles). Measurements are made every 3.0 m and after dividing the object into three rows. The obtained data are averaged. Units of measurement – 1 lux (lx).

LMT L 1003 is a luminance measuring camera, which can be used to measure the luminance of the installed lighting in outdoor conditions in a selected object.

The LMT L 1003 Luminance meter differs from the Lumicam 1300 Mono in that it cannot immediately capture the light intensity of the entire measured area. Measurements are made on a selected specific point on the road surface. The number of selected measurement points per traffic lane is 30. The points are arranged in three rows of 10 points each. The size of the measured object can be up to 40.0–60.0 m long and the entire width of the roadway. Measurements are made from a height

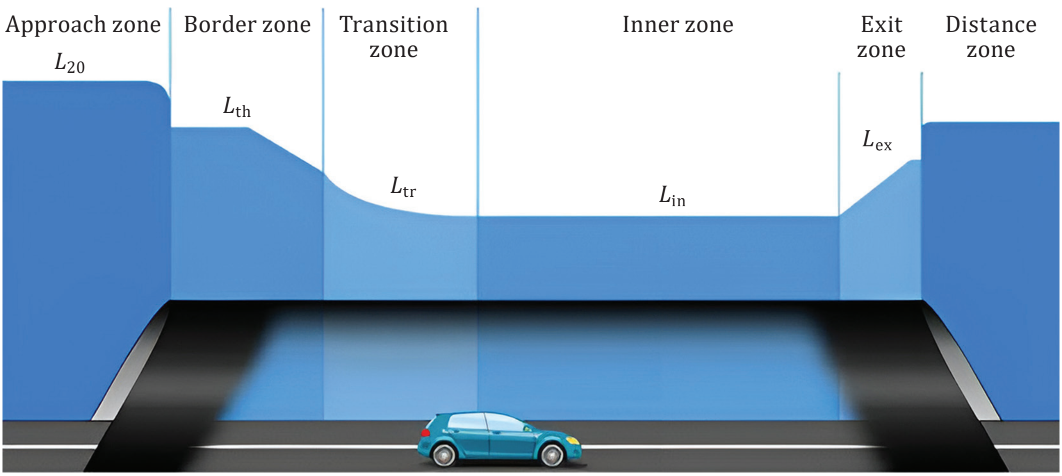

Figure 1. Division of the road tunnel into lighting zones (Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020)

of 1.20–1.50 m. The obtained data are entered into Microsoft Excel tables and mathematical calculations are performed to calculate L_{vid}, U_0, U_l.

Each road tunnel is unique, with different dimensions, permissible traffic speeds, and other characteristics. Road tunnel lighting can be categorized into two groups: approach lighting and road tunnel lighting, each with specific requirements. The selection of a lighting system typically begins with dividing the tunnel into lighting zones of varying lengths. Five zones are typically recognized for tunnel lighting (Figure 1) (Liu, 2005; Rands, 2016; Tunnel lighting, 2015; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

Approach zone: This zone covers the lighting on roads and streets before entering the tunnel.

Border zone: This area provides illumination for the boundary zone, allowing drivers to see the inside of the tunnel from the approach area.

Transition zone: Following the border zone, this is the second lighting zone with tunnel lighting, helping to illuminate the transition zone and adapt the driver's eyes to the brightness level of the inner zone.

Inner zone: The third lighting zone following the entrance zone (transition zone), with predominant lighting that ensures sufficient visibility inside the tunnel, regardless of whether the vehicle main headlights are in use.

Exit zone: This is the last lighting zone of the tunnel, starting from the end of the entrance zone and continuing to the end of the tunnel. It features lighting that illuminates the exit lane and enhances driver visibility when transitioning from the inner zone to the area beyond the tunnel. Each lighting zone is defined by its light intensity/characteristics measured in candelas.

Luminance of the road surface of the approach zone L_{20}: the average luminance of a cone-shaped field of vision limited by an apex angle of 20°. The apex of this cone is located at the centre of the oncoming driver's eye, with the centre positioned at approximately one-quarter of the height of the entrance portal; L_{20} is determined from a distance equal to the entire stopping distance before entering the tunnel at the centreline of the road or lane.

Border zone road surface luminance L_{th}: average road surface luminance at the beginning of the border zone (as a function of the calculation field of the corresponding space – valid for all luminance values listed below).

Luminance of the surface of the road surface of the transition zone L_{tr}: the average brightness of the road surface in a specific location within the transition zone.

Inner zone road surface luminance L_{in}: average road surface luminance within the inner zone.

Exit road surface luminance L_{ex}: average road surface luminance within the exit zone.

When designing the lighting for a new road tunnel and determining the luminance of the road surface in the L_{20} boundary zone, it is necessary to apply a method based on the analysis of the 20° conical field of view (Figure 2) (Liu, 2005; Liang et al., 2016; Rands, 2016; Tunnel lighting, 2015; Peña-García, 2019; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

Since the luminance value of the road surface of the boundary zone is unknown, and the percentage of the approach lane τ is small, these values can be ignored and the resulting luminance of the L_{20} road surface can be determined according to the Equation (2). The L_{20} luminosity value determined by this method is the maximum value that can be corrected from data analysis of the L_{20} relative abundance distribution. The coefficients γ, ρ, ε are determined using tunnel entry sketches or a photograph from a distance equal to the entire stopping distance before entering the tunnel (Equation (1)) (Rands, 2016; Peña-García, 2019; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

$$S = \frac{v^2}{2\mu g}, \tag{1}$$

where S – braking distance, km; v – speed, km/h; μ – a coefficient of friction: when dry asphalt – 0.70, when wet asphalt – 0.40, when paving with compressed now – 0.20; g – acceleration of free fall – 9.80 m s^{-2}.

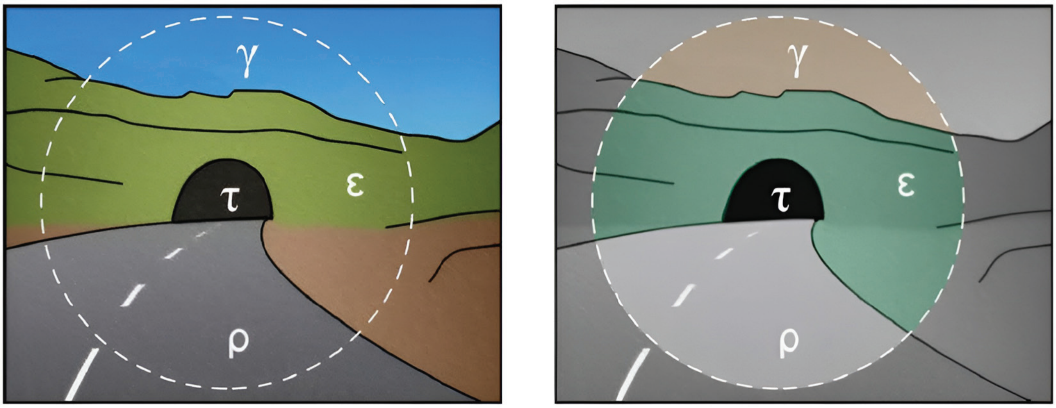

Figure 2. An example of a tunnel portal image with a 20° field of view and separate parts of the field: τ (Tau) – percentage of the approach lane; γ (Gamma) – the percentage of sky; ρ (Rho) – the percentage of the carriageway of the road; ε (Epsilon) – the percentage of the environment (Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020)

If it is not possible to measure the brightness of L_C, L_R, L_E, the values are determined according to the direction of travel, the landscape, and the environment (Rands, 2016; Peña-García, 2019; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020):

$$L_{20} = \gamma L_C + \rho L_R + \varepsilon L_E, \quad (2)$$

where L_{20} – the luminance of the road surface of the boundary zone, cd/m^2; L_C – the illumination of sky; L_R – the illumination of road; L_E – the illumination of environment; γ – the percentage of sky; ρ – the percentage of roadway; ε – the percentage of environment.

Motorway tunnels are subject to the same lighting classes as roads. Lighting classes are divided according to certain lighting zones: motorized transport zones (M), conflict zones (C), crossings and low-speed zones (P) (Liang et al., 2020). To determine the appropriate lighting class for designed road tunnels, knowledge of the prevailing traffic intensity is essential (Rands, 2016; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

Illumination classes are photometric requirements aimed at ensuring the vision needs of various road users on different types of roads, streets and public spaces, taking into account environmental conditions. The higher the number next to the class letter, the lower the class. The selection of M class relevant for the study is presented in Tables 2 and 3.

It should be noted that the brightness uniformity of lighting class tunnels at night must meet the same requirements as during the day. This also applies to tunnels longer than 100.0 m that are not illuminated during the day (Tunnel lighting, 2015; Rands, 2016; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

Table 1. Approximate luminance values (kcd/m^2) in different tunnel accesses and environments in a 20° field of view (Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020)

Travel directions	L_C (from sky)	L_R (roadway)	L_E (environment)			
			Rocks	Buildings	Snow	Meadows
Northerly	8	3	3	8	15 (V, H)	2
Easterly and Westerly driving in	12	4	2	6	10 (V) 15 (H)	2
Southerly	16	5	1	4	5 (V) 15 (H)	2

Note: (V) marked values are selected for mountainous landscapes where steep areas prevail; Values marked in (H) are selected for flat landscapes.

To avoid the black hole effect (Buraczynski at al., 2010) and meet the minimum requirements for adequate visibility of obstacles and other elements in the road tunnel boundary zone, the luminance of the road surface in the boundary zone must reach certain minimum values. These values are contingent on the luminance of the road surface in the L_{20} approach zone, representing the average luminance below which the road surface brightness should not decrease. This determination applies to the entire width of the road tunnel, encompassing traffic lane(s) and emergency lane(s) if present within the tunnel.

The luminance L_{th} of the boundary zone road surface (Rands, 2016; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020) can be determined as follows:

$$L_{\text{th}} = k \cdot L_{20}, \tag{3}$$

Table 2. Motorized transport lighting zones M (Lithuanian Standards Board, 2016)

Lighting Classes	Illumination of the road surface of the carriageway in dry and wet conditions				Threshold Increment	Ambient Lighting
	Dry Conditions			Wet	Dry Conditions	
	$\overline{L}$ (minimum value) cd/m^2	U_0 (minimum value)	U_l (minimum value)	U_0 (minimum value)	f_{TI}[c] (minimum value)	R_{EI}[d] (minimum value)
M1	2.00	0.40	0.70	0.15	10	0.35
M2	1.50	0.40	0.70	0.15	10	0.35
M3	1.00	0.40	0.60	0.15	15	0.30
M4	0.75	0.40	0.60	0.15	15	0.30
M5	0.50	0.35	0.40	0.15	15	0.30
M6	0.30	0.35	0.40	0.15	20	0.30d

Table 3. Conflict lighting zones C (Lithuanian Standards Board, 2016)

Lighting Classes	Horizontal Illuminance	
	$\overline{E}$[a] (minimally supported), lx	U_l (minimum value)
C0	50.0	0.40
C1	30.0	0.40
C2	20.0	0.40
C3	15.0	0.40
C4	10.0	0.40
C5	7.50	0.40

where k is the ratio of the illumination of border zone L_{th} and of the luminance of approach zone L_{20}.

The length of the border zone equals the entire stopping distance. In the first half of the length, the road surface brightness L_{th} remains constant, similar to the beginning of the boundary zone. In the second half, the luminance L_{th} of the road surface should linearly decrease to a value of approximately $0.4L_{th}$ (Rands, 2016; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

In the transition zone, the brightness level of the road surface decreases according to the curve shown in Figure 6. The transition zone starts at the end of the boundary zone (t = 0). The decrease in luminance of the road surface when moving from the transition zone to the inner zone follows a 3:1 ratio.

The following dependence is applied to the decrease in the brightness level of the road surface, as shown in Figure 3 (Rands, 2016; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020):

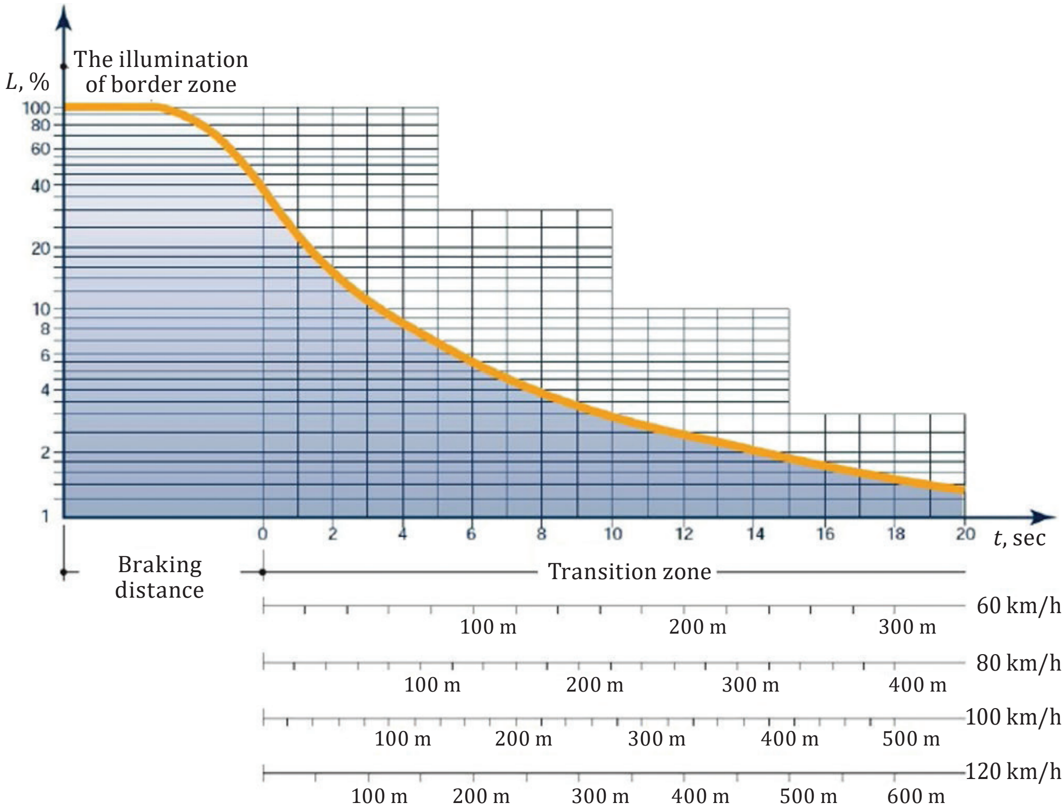

Figure 3. Luminance of the road surface in the border and transition zones (Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020)

$$L_{tr} = L_{th}\left(1.9 + t\right)^{-1.4}, \quad (4)$$

where L_{tr} – the luminance of the road surface of the border zone, cd/m^2;
L_{th} – marginal luminance of the road surface in the zone, cd/m^2, is 100.0% of value; t – time, s.

The inner zone of the tunnel is illuminated with the weakest lighting. Lighting design in this zone is based on the design speed and lighting classes. For lighting classes 1–3, the average luminance of the road surface in the emergency lanes may be lower than in the adjacent lane(s) (Tunnel lighting, 2015; Rands, 2016; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

The final zone of the tunnel is the exit zone, with its length in meters usually being equal to the speed in km/h. The lighting level here is 5 times higher than the lighting level in the inner zone. The adaptation of eyes to increasing light levels is faster, and exit lighting aids visibility when leaving the tunnel, preventing smaller vehicles from hiding behind trucks in the tunnel in front of the bright exit portal during the day (Tunnel lighting, 2015; Rands, 2016; Ministerstvo dopravy a výstavby Slovenskej Republiky, 2020).

The lighting of car road tunnels is also greatly influenced by factors such as the colour of the walls (preferably light colours), the colour and smoothness of the road surface (smoother surfaces reflect light more regularly). The determined brightness uniformity is ensured on the surface of the road surface and walls up to a height of 2.0 m. The road surface and the lower parts of the walls serve as a backdrop for tunnel users and are therefore essential for evaluation (Liu, 2005).

Modern lighting design needs to be sustainable, considering technical requirements in each country and economic principles. Currently, LED lights are used in road tunnels, meeting general requirements while differentiating those specific to tunnel lighting and the tunnels themselves.

2. Experimental study of lighting in road tunnels

2.1. Research object

Experimental studies are important when selecting lighting technology for road tunnels, determining whether the installed lighting meets the minimum lighting requirements valid in that country, ensuring quality and the longest possible lamp lifespan.

Three road tunnels in Vilnius, namely Liepkalnis St. intersections (located at Liepkalnis St. and Minsk Hwy.), Gudeliai (located at the end of the Western bypass at Oslo St.), and Gelezinio Vilko St. (located under the Parliament of the Republic of Lithuania on Gediminas Avenue) were selected for experimental research measurements (Figure 4). Table 4 provides an overview of the key characteristics of these tunnels.

2.2. Experimental equipment and study description

To determine whether the lighting level in the selected object meets the minimum requirements specified by the LST EN 13201-2:2016 lighting standard, measurements are conducted under optimal

Table 4. The technical characteristics of Liepkalnis St. intersection tunnel, Gudeliai tunnel and tunnel of Gelezinio Vilko St.

Tunnel name	Permissible vehicle speed, km/h	Tunnel lighting class	Tunnel length, m	Tunnel width, m	Tunnel height, m	Traffic volume, cars/h
Tunnel of Liepkalnis St. intersection	60.0	4	80.0	18.0	5.50	1500
Gudeliai tunnel	70.0	4	150.0	34.40	6.68–7.26	1500
Tunnel of Gelezinio Vilko St.	60.0	4	355.0	27.80	5.52	1500

Figure 4. Locations of tunnels under consideration

conditions, including low traffic volume (< 500 vehicles/hour for one-way traffic or < 100 vehicles/hour for two-way traffic) and good weather conditions (clear day or night).

Measurements are conducted during both day and night. A LMT L 1003 Luminance meter, equipped with a camera, is used for assessing lighting quality (see Figure 3). The camera can measure the luminance of the installed lighting in outdoor conditions. However, it cannot capture the entire area's light volume at once, so measurements are taken at specific points on the road surface. The equipment used for luminance measurement is calibrated.

The measurement area consisted of 38.0–45.0 m length and the entire roadway. The measurements are carried out as follows: one engineer with the meter stands on the traffic lane and points the meter at the asphalt pavement as indicated by another engineer (typically every 3.80–4.50 m, depending on the selected length). This determines the measurement points.

For each traffic lane, 10 points are measured over the entire length of the measurement area (38.0–45.0 m), and three points are measured across the width of the traffic lane, resulting in a total of 30 points in a single traffic lane. After measuring the entire area, the measuring device is moved to the middle of the adjacent traffic lane and the measurement is performed again. The measurement is repeated for each lane on the roadway. The results obtained are then averaged to determine the uniformity of lighting in the measured areas.

1–3 observers (engineers) stand in the middle of the traffic lane with measuring device, measuring lighting at the points indicated by another engineer conducting the measurements. The written numbers indicate how many times the measurement is performed in the intended area.

2.3. Results of road tunnel lighting research

Road surface luminance measurements are performed according to LST EN 13201-2:2016 lighting standard.

Tunnel lighting parameters 1.50–3.0 cd/m^2 at night:

L_{min} > 1.50 luminance of the road pavement, cd/m^2,

U_0 > 0.40 – overall luminance uniformity, $L_{min}/L_{av.}$,

U_l > 0.70 – longitudinal luminance uniformity L_{min}/L_{max}.

Liepkalnis tunnel

The power of the lights installed in Liepkalnis tunnel is 14.10 kW, with a total of 176 built-in lamps.

As seen in diagram (Figure 6) and in accordance with the LST EN 13201-2:2016 lighting standard, it can be concluded that the luminance of the road pavement exceeds the minimum (1.50–3.0 cd/m^2) requirements in all phases and the tunnel can be operated safely.

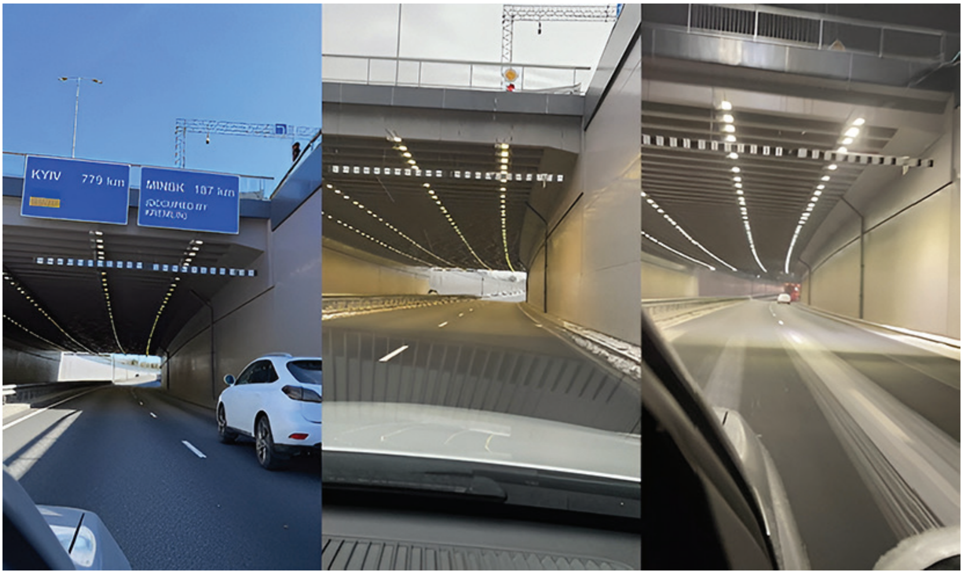

Figure 5. Liepkalnis tunnel lighting at different times (from left to right: sunny, cloudy and night)

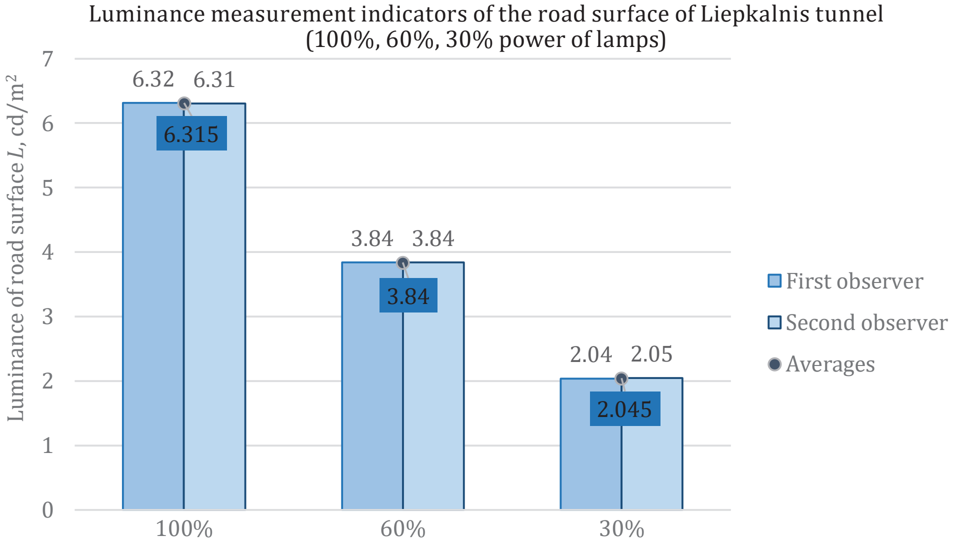

Figure 6. The results of measuring the luminance of the road pavement of Liepkalnis tunnel

Gudeliai tunnel

The power of the lamps installed in Gudeliai tunnel is 227.40 kW, and there is a total of 618 built-in lamps.

Based on the provided diagram (Figure 8) and in accordance with the LST EN 13201-2:2016 lighting standard, it can be affirmed that the luminance of the road surface meets or exceeds the minimum requirements in all phases, ensuring safe operation of the tunnel.

Figure 7. Lighting of Gudeliai tunnel under different conditions (from left to right: sunny, cloudy and night)

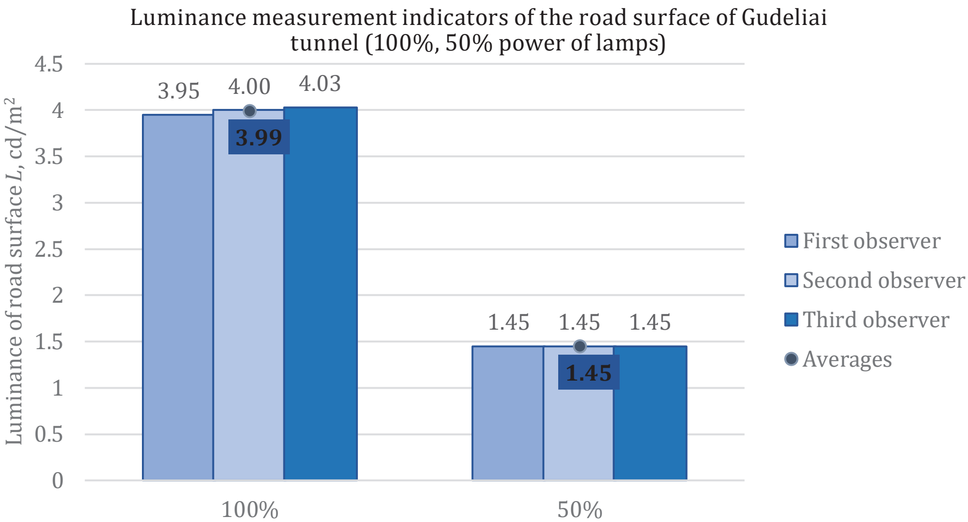

Figure 8. The results of measuring the road surface luminance in Gudeliai tunnel

Gelezinio Vilko street tunnel

The power of the lamps installed in the tunnel of Gelezinio Vilko street is 105.50 kW, and there is a total of 410 built-in lights.

In line with the provided diagram (Figure 10) and following the LST EN 13201-2:2016 lighting standard, it can be affirmed that the luminance of the road surface meets or exceeds the minimum requirements in all phases, ensuring the safe operation of the tunnel.

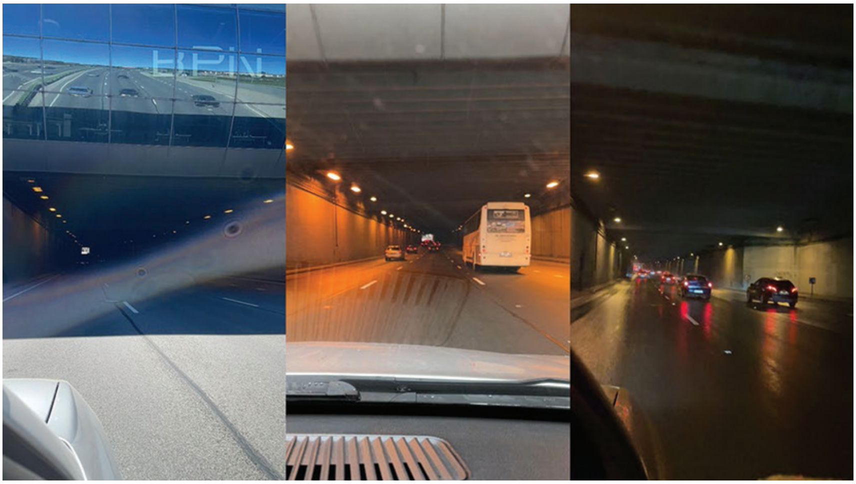

Figure 9. Gelezinio Vilko street tunnel lighting under different conditions (from left to right: sunny, cloudy and night)

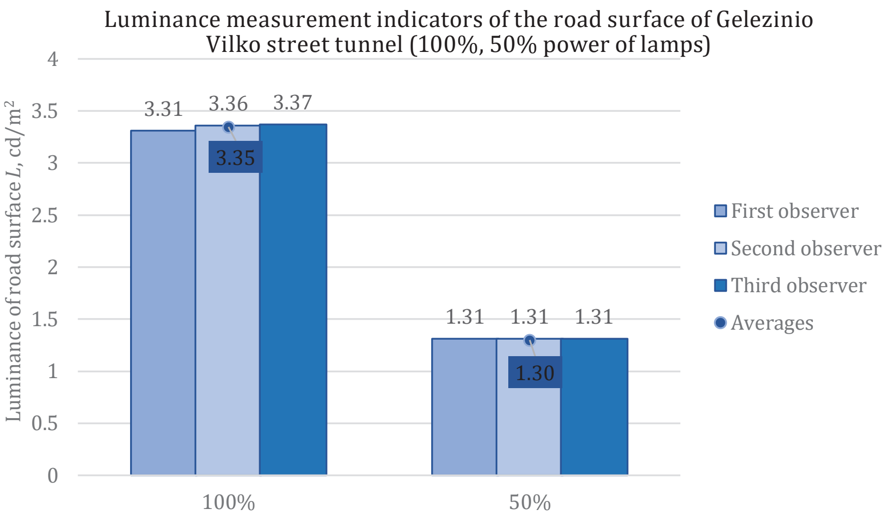

Figure 10. The results of measuring road surface luminance on Gelezinio Vilko St. tunnel

3. Analysis and interpretation of road tunnel survey data

3.1. Results-based modelling of road tunnel lighting

Liepkalnis tunnel

According to the lighting measurement indicators, the Liepkalnis tunnel has installed LED-type lamps with higher power than necessary. According to the data of the company responsible for lighting in Vilnius (Closed joint stock company "Vilnius illumination"), the lights operate at no more than 90.0% strength on sunny days. Taking into account the fact that the tunnel has no lighting zones (it is only 80.0 m long), it is recommended to replace the existing LED-type lamps with new 67.0 W LED-type lamps with asymmetric lighting.

Gudeliai tunnel

Taking into account the measurement data, the type of existing lamps and their age, it is recommended to replace the current sodium-type lamps with LED lamps. Newly designed luminaires should be equipped with luminous flux regulation, allowing for dimming to 100.0%, 60.0% and 30.0% of the operating mode if required.

Figure 11. View of the portal of Gudeliai tunnel from the south side with a 20° field of view and individual parts of the field

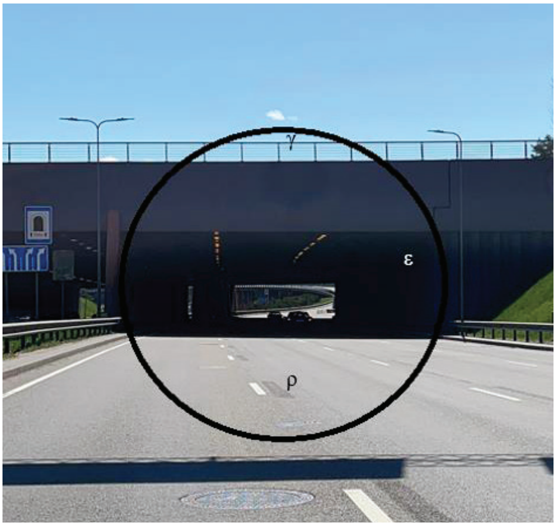

Figure 12. View of the portal of the Gudeliai tunnel from the north side with a 20° field of view and individual parts of the field

Calculation and values

The luminance values of the road surface of each part of the Gudeliai tunnel were determined (Figure 12) and the luminance of the road surface L_{20} (Equition (2)) was calculated. Thus, the luminance of the road surface of the boundary zone (first part) L_{th} (Equition (3)) was calculated. After calculating the luminance L_{th} (Equition (3)) of the road surface of the border zone (first part), the luminance L_{th} and length l_{th} of the road surface of the border zone (second part) and the luminance L_{tr} (Equition (4)) and length l_{tr} of the road surface of the exit zone were calculated.

The proposed LED-type luminaires that could emit the required light intensity would be of two types with an asymmetric optical system (He et al., 2017a, b; Peña-García, 2019; Shi et al., 2016). The quantities of each type are as follows:

- 508.0 W – 112 units;
- 264.0 W – 72 units;
- 2.0 W – 28 units.

LED-type luminaires with an asymmetric optical system (otherwise known as counter-beam lights) create a greater contrast between objects and the background of the roadway than with symmetrical light distribution. Luminaires of this type are most effective when it is necessary to provide high or increased tunnel lighting required at the threshold of the tunnel and in the transition areas of the tunnel, where they are installed as little as possible.

Table 5. Recommended lighting for the Gudeliai tunnel based on calculated values

Luminaire type and power, W	Quantity of luminaires, units	L_{20}, cd/m^2	L_{th}, cd/m^2 (first part)	L_{th}, cd/m^2 (second part)	l_{th}, m	L_{tr}, cd/m^2	l_{tr}, m	k value	S, m
Southern side of Gudeliai tunnel									
508.0 (LED)	56	5800.0	290.0	116.0	30.0	15.0	70.0	0.05	50.0
264.0 (LED)	36								
2.0 (LED)	14								
Northern side of Gudeliai tunnel									
508.0 (LED)	56	5000.0	250.0	100.0	30.0	15.0	70.0	0.05	50.0
264.0 (LED)	36								
2.0 (LED)	14								

Consideration of the tunnel environment is also essential for enhancing lighting and ensuring the comfort of road users. The proposal includes directional two-way LED lights on technical sidewalks to improve visibility along the carriageway during both day and night.

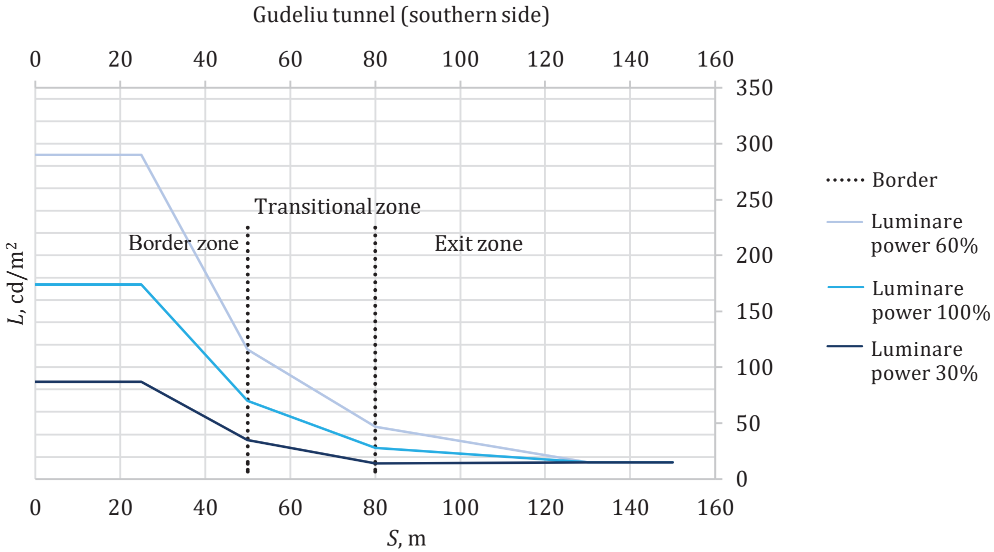

Figure 13. The luminance of Gudeliai tunnel road pavement calculated driving from South to North (Compiled by the authors based on calculations)

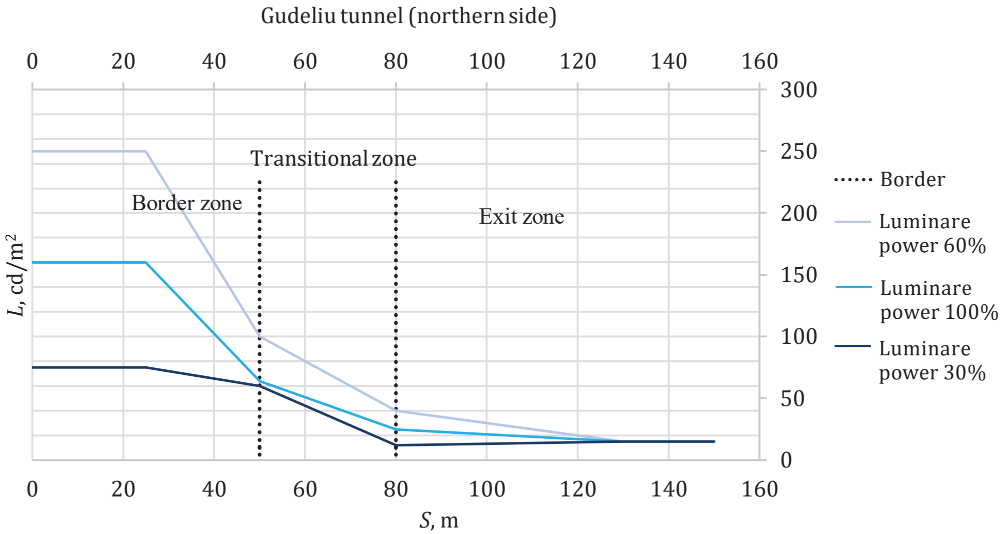

Figure 14. The luminance of the road pavement surface of Gudeliai tunnel calculated driving from North to South (Compiled by the authors based on calculations)

Tunnel of Gelezinio Vilko St.

Considering the measurement data, the type of existing luminaires, and their age, it is recommended to replace the existing sodium-type luminaires with light-emitting diode (LED) luminaires. The newly designed luminaires should be equipped with luminous flux regulation, allowing them to be dimmed to 100.0%, 60.0% and 30.0% of the operating mode if required.

Table 6. Recommended lighting for the Gelezinio Vilko St. tunnel based on calculated values

Luminaire type and power, W	Quantity of luminaires, units	L_{20}, cd/m²	L_{th}, cd/m² (first part)	L_{th}, cd/m² (second part)	l_{th}, m	L_{tr}, cd/m²	l_{tr}, m	k value	S, m
Southern side of Gelezinio Vilko St. tunnel									
415.0 (LED)	74								
250.0 (LED)	78	4500.0	225.0	90.0	259.0	15.0	60.0	0.05	36.0
2.0 (LED)	30								
Northern side of Gelezinio Vilko St. tunnel									
415.0 (LED)	74								
250.0 (LED)	78	5500.0	275.0	110.0	259,0	15.0	60.0	0.05	36.0
2.0 (LED)	30								

Figure 15. Gelezinio Vilko St. view of the tunnel portal from the southern side with a 20° field of view and individual parts of the field

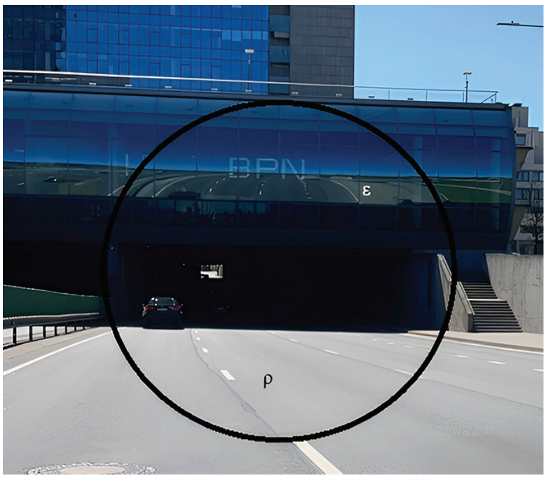

Figure 16. Gelezinio Vilko St. view of the tunnel portal from the north side with a 20° field of view and individual parts of the field

The proposed LED-type luminaires that could emit the required light intensity would be of two types with an asymmetric optical system tilted at an angle of 10–80° (He et al., 2017a,b; Peña-García, 2019; Shi et al., 2016):

– 415.0 W – 148 units;
– 250.0 W – 156 units;
– 2.0 W – 60 units.

The environment of the tunnel has also been taken into account when improving the lighting conditions of the tunnel and ensuring the comfort of road users driving along the tunnel.

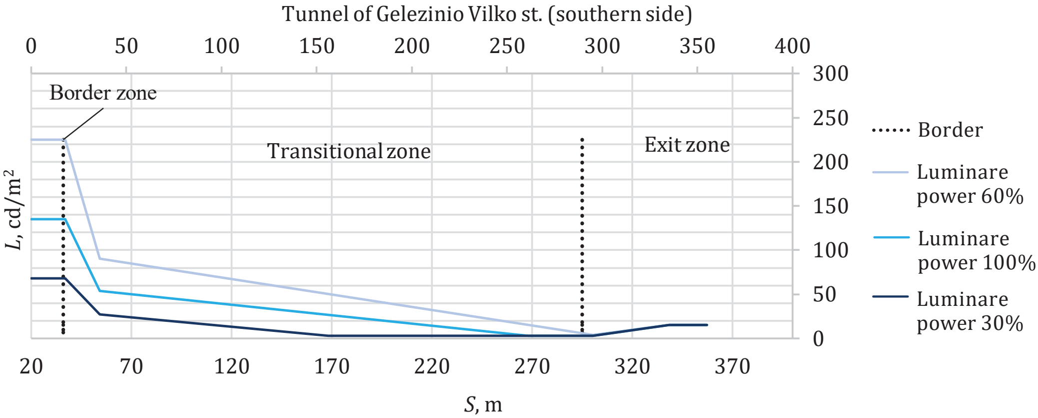

Figure 17. The luminance Gelezinio Vilko St. tunnel road pavement surface calculated driving from south to north (Compiled by the authors based on calculations)

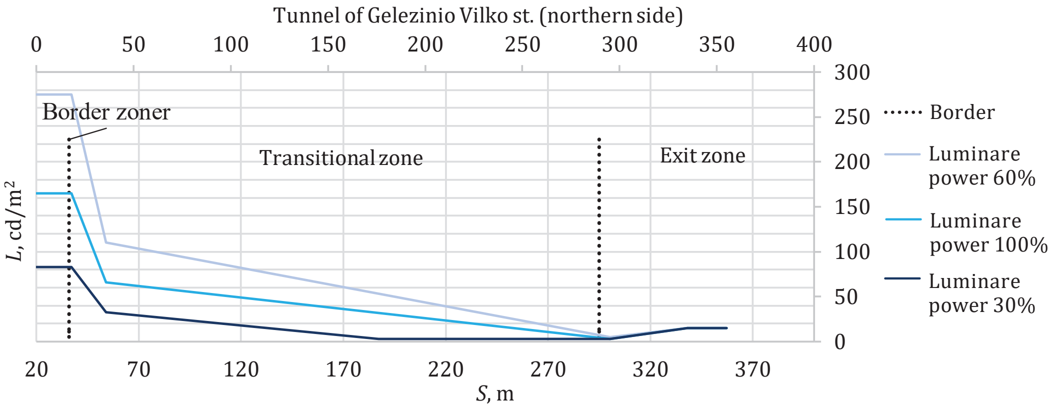

Figure 18. The luminance of Gelezinio Vilko St. tunnel road pavement surface calculated driving from north to south (Compiled by the authors based on calculations)

It is proposed to provide directional two-way LED lights on technical sidewalks so that vehicle drivers can easily see the edges of the roadway both during the day and at night. It is also proposed to plan for smoothing the inner walls and ceiling of the tunnel with a finishing layer of concrete and concrete impregnates. In order to reduce the need for LED lights, it is suggested to paint the walls in RAL 9006 white aluminium colour, due to the high light reflection (solar reflection 0.616), thus creating a comfortable environment.

Conclusions

High-quality road tunnel lighting is an important factor in ensuring and improving safe and suitable conditions for car travel. Well-equipped lighting can reduce unnecessary stressful situations, improve the presentation of information to drivers of traffic vehicles, and ensure uniform visibility of the entire road tunnel area, comfort and safety of drivers.

The road tunnel is divided into four lighting zones – boundary, transition, internal and exit zone. Short road tunnels may have fewer lighting zones, and sometimes a single lighting zone prevails throughout the entire tunnel.

Three road tunnels in the city of Vilnius were selected for the study. Measurements of lighting quality during both day and night were performed. Measurements were made with LMT L 1003 Luminance meter. The measurement area consisted of 38.0–45.0 m tunnel length and the entire width of the roadway. The obtained results were averaged, and the uniformity of light in the measured areas was determined in L_{av}.

Surface luminance measurements of road tunnels were performed:

Liepkalnis tunnel – $L_{av} = 6.32$ cd/m^2 (illumination power – 100.0%), $L_{av} = 3.84$ cd/m^2 (60.0%), $L_{av} = 2.04$ cd/m^2 (30.0%); Gudeliai tunnel – $L_{av} = 3.99$ cd/m^2 (100.0%), $L_{av} = 1.45$ cd/m^2 (50.0%); Gelezinio Vilko St. tunnel – $L_{av} = 3.35$ cd/m^2 (100.0%), $L_{av} = 1.30$ cd/m^2 (50.0%).

In accordance with the LST EN 13201-2:2016 street lighting standard for the M2 (≥1.50 cd/m^2) street class, the lighting of Liepkalnis tunnel meets the requirements, while the lighting of Gudeliai and Gelezinio Vilko St. tunnels do not meet the lighting requirements. Road tunnel lighting renewal solutions are recommendable.

Calculations of the road surface luminance of selected tunnels were performed and recommendations were made for renewing the lighting of the road tunnels. Liepkalnis tunnel had 176 units 80.0 W LED lamps. Based on calculations, it is recommended to install 176 units of 67.0 W power LED lights. Gudeliai tunnel had 558 units of 400.0 W and 60 units of 70.0 W sodium lamps. Based on calculations, it is recommended to install 112 units of 508.0 W, 72 units of 264.0 W and 28 units of 2.0 W LED lamps in this tunnel. The tunnel of Gelezinio Vilko St. had 192 units of 400.0 W, 34 units of 250.0 W, 36 units of 150.0 W and 148 units of 100.0 W sodium lamps. It is recommended to install 148 units of 415.0 W, 156 units of 250.0 W and 60 units of 2.0 W LED lamps.

Savings are expected after renovation works: 10.0–20.0% less energy consumption in Liepkalnis tunnel; 70.0–80.0% less energy consumption in Gudeliai tunnel; 50.0–60.0% less energy consumption in the tunnel of Gelezinio Vilko St.; between 10.0–80.0% electricity savings can be realized by replacing sodium-type lamps with LED-type lamps.

Recommendations for improving the lighting of the tunnels are presented after performing the measurements of the lighting of the tunnels in question and following the valid technical regulations of road tunnel lighting in other countries. These recommendations could be used as a guide when preparing a Lithuanian regulatory document for the design and installation of road tunnel lighting.

Recommendations/proposals for improving road tunnel lighting

Improving road tunnel lighting is a critical consideration for all road users. The primary design principles for road tunnel lighting represent initial steps that could be incorporated into the development of technical regulations for the design and installation of road tunnel lighting:

- The primary objective of lighting is to ensure both safe and comfortable traffic within the tunnel and its approaches.
- The lighting should be modern, remotely controlled, and cost-effective. It is expected to be implemented through the use of LEDs.
- Tunnels that are not illuminated during the day should be limited to a maximum length of 50.0 m.
- Tunnels of up to 100.0 m should not be divided into lighting zones.
- Double-sided orientation or marking LED lights should be positioned at the edges of technical sidewalks and within the boundaries of horizontal markings.
- Employing smooth, well-lit walls, up to 2.0 m in height, with architectural lighting, is a guarantee of a comfortable and high-quality lighting environment.
- For an 80.0-meter-long tunnel with two traffic lanes (in both directions) and a width of 3.75 m (a tunnel with a single zone), 176 units (arranged in two rows for each traffic direction) of 67.0 W LED-type lamps are sufficient. For tunnels that are longer or wider, additional measurements and calculations are necessary to determine the optimal lighting.

REFERENCES

Avotins, A., Adrian, L. R., Porins, R., Apse-Apsitis, P., & Ribickis, L. (2021). Smart city street lighting system quality and control issues to increase energy efficiency and safety. *Baltic Journal of Road & Bridge Engineering*, *16*(4), 28–57. https://doi.org/10.7250/bjrbe.2021-16.538

Buraczynski, J. J., Li, T. K., Kwong, C., & Lutkevich, P. J. (2010). Tunnel lighting systems. *Tunnelling Safety and Security*, *56*, 553–556. https://www.scribd.com/doc/282919917/554-557-Tunnel-Lighting-Systems-pdf

He, S. Y., Tähkämö, L., Maksimainen, M., Liang, B., Pan, G. B., & Halonen, L. (2017a). Effects of transient adaptation on drivers' visual performance in road tunnel lighting. *Tunnelling and Underground Space Technology*, *70*, 42–54. https://doi.org/10.1016/j.tust.2017.07.008

He, S., Liang, B., Pan, G., Wang, F., & Cui, L. (2017b). Influence of dynamic highway tunnel lighting environment on driving safety based on eye movement parameters of the driver. *Tunnelling and Underground Space Technology*, *67*, 52–60. https://doi.org/10.1016/j.tust.2017.04.020

Liang, B., He, S., Tähkämö, L., Tetri, E., Cui, L., Dangol, R., & Halonen, L. (2020). Lighting for road tunnels: The influence of CCT of light sources on reaction time. *Displays*, *61*, Article 101931.
https://doi.org/10.1016/j.displa.2019.101931

Lithuanian Standards Board. (2016). *LST EN 13201-2:2016: Kelių apšvietimas. 2 dalis. Eksplotacinių charakteristikų reikalavimai* [Road Lighting. Part 2. Methods of Measuring Operational Characteristics].

Liu, H. Y. (2005). Design criteria for tunnel lighting. *World Long Tunnels 2005*, 363–372. https://www.semanticscholar.org/paper/DESIGN-CRITERIA-FOR-TUNNEL-LIGHTING-Liu/28f6513ae38ab3b6d8bf9917b14cc2d21687a96a

Lunkevičiūtė, D., Vorobjovas, V., Vitta, P. & Čygas, D. (2023). Research of the luminance of asphalt pavement in trafficked areas. *Sustainability*, *15*(3), Article 2826. https://doi.org/10.3390/su15032826

Ministerstvo dopravy a výstavby Slovenskej Republiky. (2020). *Technické Podmienky. Osvetlenie cestných tunelov* (Ministry of transport and transport of the Slovenskej Republiky). https://www.ssc.sk/files/documents/technicke-predpisy/tp/tp_115_2020.pdf

Pachamanov, A., & Pachamanova, D. (2008). Optimization of the light distribution of luminaries for tunnel and street lighting. *Engineering Optimization*, *40*(1), 47–65. https://doi.org/10.1080/03052150701591160

Peña-García, A. (2019). Optical coupling of grouped tunnels to decrease the energy and materials consumption of their lighting installations. *Tunnelling and Underground Space Technology*, *91*, Article 103007.
https://doi.org/10.1016/j.tust.2019.103007

Rands, J. (2016). Road tunnel lightint guide. Guide to the lighting of road tunnels in Armenia. https://www.scribd.com/document/362442981/Road-Tunnel-Lighting-Guide

Shi, N., Dong, L., Qin, L., & Xu, W. (2016). Study on lamp-layout scheme of highway tunnel lighting based on DIALux. *2016 5th International Conference on Energy and Environmental Protection (ICEEP 2016)*, 773–781. https://doi.org/10.2991/iceep-16.2016.133

Tunnel lighting. (2015, August 04). Thorn. Publication No: 283(INT). https://www.thornlighting.com/download/TunnelINT.pdf

Vilnius Lighting. (2023). https://www.vilniausapsvietimas.lt/

Zhao, J., Feng, Y., & 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*, Article 103768. https://doi.org/10.1016/j.tust.2020.103768

Yoomak, S., Jettanasen, C., Ngaopitakkul, A., Bunjongjit, S., & Leelajindakrairerk, M. (2017). Comparative study of lighting quality and power quality for LED and HPS luminaires in a roadway lighting system. *Energy and Buildings*, *159*, 542–557. https://doi.org/10.1016/j.enbuild.2017.11.060