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Revision of Threshold Luminance Levels in Tunnels Aiming to Minimize Energy Consumption at No Cost: Methodology and Case Studies †

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Abstract: Because of the absence of lighting calculation tools at the initial stage of tunnel design, the lighting systems are usually over-dimensioned, leading to over illumination and increased energy consumption. For this reason, a fine-tuning method for switching lighting stages according to the traffic weighted L20 luminance is proposed at no additional cost. The method was applied in a real –case scenario, where L20 luminance of the access zone at eleven (11) existing tunnels was calculated. The traffic weighted method of CR14380 was used in order to calculate the actual luminance levels for the entrance zone. The new transition zone, which decreases luminance curves, was produced and compared with the existing ones. Thus, a new switching control was proposed and programed for the Supervisory Control and Data Acquisition (SCADA) system of the tunnel. The signals of the corresponding eleven L20 meters for a period of eight days were used and the corresponding annual energy consumptions were calculated using the proposed switching program for each tunnel. The results were compared with a number of scenarios in which the existing lighting system was retrofitted with Lighting Emitting Diodes (LED) luminaires. In these scenarios, the new luminaire arrangement was based not only on the existing luminance demand value for the threshold zone, but also on the newly proposed one with two different control techniques (continuous dimming and 10% step dimming). The fine-tuning method for switching resulted in energy savings between 11% and 54% depending on the tunnel when the scenario of the existing installation at no extra cost was used. Energy savings, when LED luminaires were installed, varied between 57% (for the scenario with existing luminance demand value for the threshold zone and 10% step dimming) and 85% (for the scenario with the new calculated luminance demand and continuous dimming).

Keywords: energy savings; lighting; optimal control; performance evaluation; tunnel lighting; sustainable tunneling; threshold zone luminance; tunnel management

1. Introduction

Artificial lighting corresponds to more than 20% of the world's electricity consumption [1]. In Europe (EU28) there are more than 1.6 million km of illuminated streets that annually consume approximately 35 TWh) at a cost of $4 billion euro for the public authorities [2]. During the last decade there has been ongoing research activity focused on energy management using various types of renewable energy sources [3–5], on recycling [6], on safety [7–10], and a concentrated effort has been made for making street lighting systems sustainable [11–19] and environmentally friendly [20–22]. In addition, during the last few years, the issue of avoiding light pollution [23–28] has gained importance in technical reports [29] and expert discussions [30].

In tunnels, the use of the lighting system should guarantee a safe pass through it, not only during the night but in daytime as well. The drivers should be able to discern the presence of other vehicles and possible obstacles in the road [31,32]. The effect of the "black" hole at the entrance of the tunnel during the day must be avoided. Thus, higher luminance values are required in order to enhance the visual adaptation of the incoming drivers. The higher luminance values needed at the entrance zone are defined by standards. The required luminance values are dependent on the incident daylight on the surrounding surfaces adjacent to the entrance. As mentioned above, visual adaptation demands increased illuminance not only at the tunnel entrance but also for a considerably long distance inside the tunnel all the way up to the interior zone. Unlike buildings, where daylight minimizes lighting needs [33–35], in tunnels it results in an increased number of installed luminaires as well as in increased power consumption for each luminaire [31,32]. This design approach increases energy consumption during the day, since the threshold luminance (Lth) is directly linked to the access zone luminance, which is represented by L20. The latter is defined as the luminance of the tunnel entrance surrounding areas within a conical field of view of 20°, within stopping distance of design speed. It is evident that the variation of daylight throughout the day affects L20 and, thus, the required luminance values inside the threshold zone. Consequently, the control of the active lighting stages of the tunnel is crucial for minimizing energy consumption during the day.

In an effort to minimize the initial costs, the decision-making process of designing a tunnel takes into consideration only the construction costs. The life cycle cost analysis, which also takes into account the maintenance and lighting operational costs, is ignored. Moretti, Cantisani, and Di Mascio compared the expected costs for pavement construction, maintenance, and road lighting of a highway tunnel in Rome [36]. A lighting system was tested inside a tunnel with a concrete pavement and the energy consumption was 29% lower than in a tunnel with an asphalt pavement [36]. Furthermore, Moretti, Cantisani, Mascio, and Caro investigated the life cycle costs of two different road tunnel pavements and their corresponding lighting systems [37]. López, Grindlay, and Peña-García [38] suggested a sustainability vector for the initial design of a tunnel. The vector presents the degree of sustainability and highlights the necessity for corrective actions when necessary, combining three parameters (a) energy consumption, (b) landscape integration, and (c) construction cost. An installation of semi-transparent tension structures at the entrance portal can lead to significant energy savings [39]. Another way to reduce the luminance requirements and, thus, the energy consumption is the forestation of the surroundings of the portal of tunnels. Energy consumption can be reduced by up to 50%, as long as the specific species that will be used are permitted by the climatic and hydrological conditions of the zone where the tunnel is [40]. Moreover, García-Trenas, J.C. López, and A. Peña-García [41] analyzed how changes in the vegetation at the area surrounding the tunnel entrance can contribute to energy savings for a lighting installation in an Alpine environment. The required illumination levels can also decrease by using structural measures at the approaching zones or at the tunnel mouth [42]. A pre-tunnel lighting may ensure adequate, progressive, physiological adaptation of the user's eyes when approaching the entrance of the tunnel, and contain the overall costs of the artificial lighting system throughout its service life [43].

As energy consumption has become a crucial factor for tunnel design, a number of control systems based on daylight compensation have been investigated for installation in the tunnel entrances [44–47].

Gil-Martín, Peña-García, Jiménez, and Hernández-Montes used a scale model in order to test a system with light-pipes [48]. In a follow-up study, the aforementioned authors used a heliostat to guide sunlight into the light-pipes. The results showed a remarkable improvement in the efficacy of light-pipes, in electrical energy consumption and in the number of luminaries used [49]. A semi-transparent tension structure of a polyester set was used just before the entrance to the tunnel. Hence, the threshold zone was extended towards the outside of the tunnel, in order to minimize lighting demands through the utilization of sunlight [50]. In addition, Peña-García and Gomez-Lorente investigated the installation of solar panels in the areas surrounding tunnel portals [51] while Peña-García and Gil-Martín investigated the use of pergolas for energy savings [52]. Unfortunately, the requirement of road surface uniformity was not fulfilled because the lighting levels were extremely low in the shadowed zones as compared to the sunlit zones [52]. Using a diffuser material in the spaces between the pergola beams improved the homogeneity of sunlight and, thus, energy savings [53]. Salam and Mezher [54] calculated 50% saving in the lighting electrical load with the use of shading structures in existing tunnels. However, energy savings must not be the only parameter to consider during lighting design. In very long tunnels, people's safety may depend on their reactions to the claustrophobic conditions of tunnels, which could range from stress and anxiety to distraction or fear [55].

Except for the initial design of a tunnel and the methods for reducing energy savings, the renewal, measurements [56,57], and maintenance procedures are also crucial elements for the operation of an existing tunnel. These require, among others, the redetermination of the L20 luminance. This can be realized by taking photographs of the entrance of a tunnel from a fixed point at the center of the motorway exactly from the stopping distance, a method that would require stopping or diverting the traffic completely. Lopez and Pena-Garcia [58] proposed a methodology that uses vehicle-based images and trigonometric considerations and does not affect the traffic. Shuguang [59] presented a tunnel lighting optimal control model taking into account both traffic safety and energy-saving issues. His control model takes the demand on brightness, the total average brightness, and the minimum dimming ratio of the luminaires as parameters. The role of dimming [60,61] and light control [62–64] is significant for the selection of luminaires [65–67]. Pachamanov and Pachamanova [68] presented models for the optimization of the lighting distribution of luminaries for tunnels, which allows the incorporation of the characteristics of the reflective properties of the surface of the road in order to obtain energy-efficient light distributions. Salata et al. [69] optimized energy savings considering the lighting system (High Pressure Sodium lamps (HPS) or Lighting Emitting Diodes (LED)) and the type of asphalt (traditional or special asphalt). Furthermore, Salata et al. [70] investigated whether it is possible to minimize energy demands through the usage of an automatic new control system regulating the luminous fluxes of artificial sources with respect to the variation of daylight, which is characteristic of the outdoor environment.

In general, the reduction of tunnel lighting consumption can be realized through proper optimization of the pavement or by retrofitting the lighting system with cost effective LED luminaires. However, energy savings can also be achieved a) with proper control of a tunnel's lighting system, since this is quite commonly organized in a number of active stages, and b) by reevaluating the corresponding luminance values in the threshold zone (Lth) using the L20 values. The scope of this paper is to propose a control strategy according to the new luminance level requirements based on the traffic weighted L20 method (CR14380, [31]) in existing tunnels. The early results of this method were presented in the 2019 IEEE (Institute of Electrical and Electronics Engineers) International Conference on Environment and Electrical Engineering and the 2019 IEEE Industrial and Commercial Power Systems Europe (EEEIC/I&CPS Europe), in Genova, Italy, June 11th-14th 2019 [71]. In this paper, the Over Lit Triggering Percentage (OLTP) of various circuits was defined. Eleven tunnels were examined and considerable amounts of energy savings and CO_2 emission reductions were achieved.

2. Materials and Methods

Most of the tunnels were constructed before the establishment of the European standards and prior to the advent of LEDs. Comparing the luminance requirements of the existing tunnels with the new weighted L20 method, over illumination is evident. Nowadays, that LED technology is mature, retrofitting the existing lighting system has become of particular importance. This paper presents a method that can take place before the renovation of the tunnels. This method results in significant energy savings and lower CO_2 emissions at no additional cost. In short, the actions involved are the following: (a) a new calculation method of the stopping distance, (b) the estimation of the corresponding L20 value, and (c) the programming of the Supervisory Control and Data Acquisition (SCADA) system of the tunnel. The proposed method is presented more analytically in Figure 1. The traffic weighted L20 method was used. The main influencing factors for the examined cases were medium for traffic flow (500–1500 vehicles per hour per lane for one-way traffic), and motorized traffic only. According to these two factors, the tunnel class was defined and then, as a next step, the new corresponding threshold zone luminance (Lth′) was calculated. The new Lth′ value, was used for each tunnel, in order to define the new triggering points of the lighting stages using the SCADA control system. Because of the new lower Lth′ values in comparison to the initial Lth values, the triggering points correspond to lower lighting levels and thus to lower amounts of associated energy consumption.

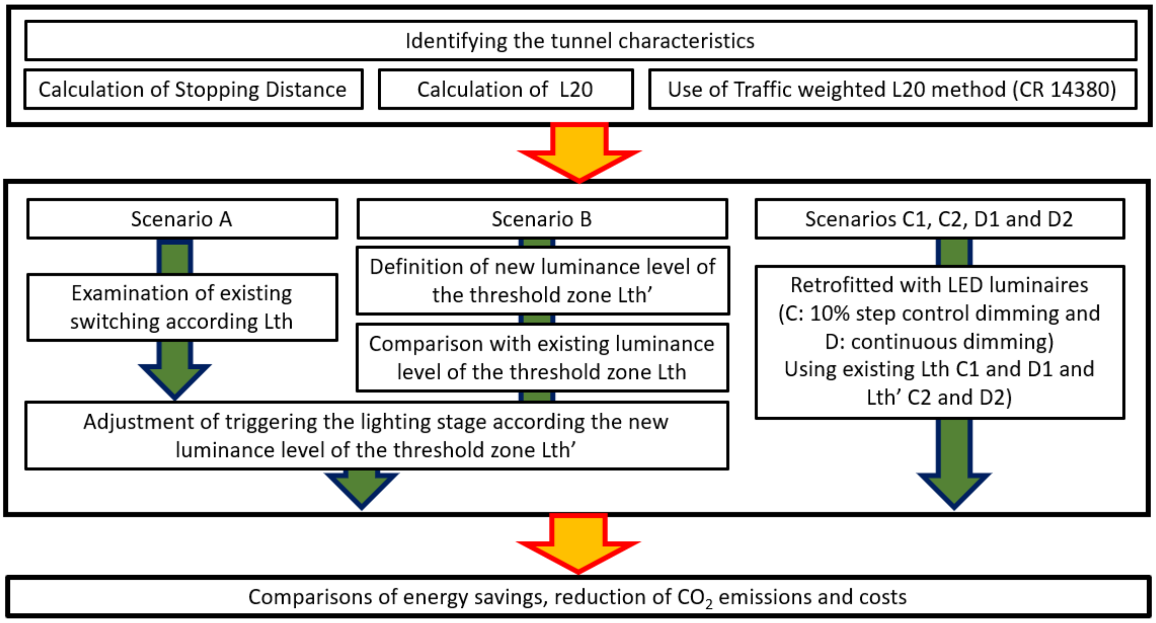

Figure 1. Diagram of the proposed methodology with the examined scenarios. Lighting Emitting Diodes (LED); threshold luminance (Lth); new corresponding threshold zone luminance (Lth′).

The following scenarios were examined:

- Scenario A: Switching control with existing Lth values.
- Scenario B: Switching control with newly calculated Lth′ values.
- Scenario C1: LED Retrofit 10% step control dimming (Lth).
- Scenario C2: LED Retrofit 10% step control dimming (Lth′).
- Scenario D1: LED Retrofit continuous dimming (Lth).
- Scenario D2: LED Retrofit continuous dimming (Lth′).

2.1. *Existing Lighting Infrastructure*

The examined case studies are part of the national motorway Patra-ATHens-Efzoni, (PATHE) in Greece. This national motorway PATHE is one of the 2 motorways connecting Athens to the rest of Greece with an approximate length of 172.5 km. The motorway starts at Metamorfossi (an area in the Prefecture of Attika) and ends at Skarfia, (Prefecture of Fthiotida), after Kamena Vourla. It is a modern motorway using international standards. This PATHE section crosses two regions and three counties and its technical features include among others, 8 bridges, 30 interchanges, 11 tunnels (Figure 2), 1 short tunnel, and 84 underpasses and overpasses.

Figure 2. The 11 examined tunnels along the national motorway Patra-ATHens-Efzoni (PATHE) in Greece.

Most of the lighting fixtures for the main road are installed at the intersections. The lighting installation of the road includes 6565 luminaires (main road, intersections, toll areas, parking sites) while the lighting fixtures for the tunnels, without taking into account the underpasses, are 5344 along 8.5 km. The basic characteristics of the eleven tunnels, which were examined together with their lighting system installed power including the power losses from the electromagnetic ballasts, are presented in Tables 1–3. The road has 2 lanes with a total lane width of 7.5 m and a speed limit of 80 km/h in the tunnels.

Table 1. The basic characteristics of the examined tunnels.

Tunnel	Length (m)	Length of Entrance Zone (m)	Length of Interior Zone (m)	Threshold Luminance Lth (cd/m^2)
1a	702.1	310.7	391.4	222
1b	656.4	308.1	348.3	175
2a	2474.7	312.0	2162.7	280
2b	2457.6	312.0	2145.6	280
3a	253.4	252.0	1.4	244
3b	253.4	250.7	2.7	290
4a	294.0	280.9	13.1	340
4b	286.7	286.7	0.0	194
5a	272.4	272.4	0.0	216
5b	273.0	268.5	4.5	303
6a	510.3	318.3	192.0	215

Table 2. Installed power and the corresponding energy indicators for the entrance zone of the examined tunnels.

Tunnel	Installed Power (kW)	Power density (W/m^2)	kW/km	Number of Luminaires	Luminaire/m	Length (m)
1a	123.8	53.1	398.4	305	0.98	310.7
1b	125.0	54.1	405.6	305	0.99	308.1
2a	126.3	54.0	404.8	306	0.98	312.0
2b	126.5	54.1	405.6	310	0.99	312.0
3a	97.0	51.3	384.8	222	0.88	252.0
3b	96.8	51.5	386.0	221	0.88	250.7
4a	134.1	63.7	477.4	290	1.03	280.9
4b	99.6	46.3	347.4	235	0.82	286.7
5a	110.2	54.0	404.6	262	0.96	272.4
5b	123.2	61.2	458.8	334	1.24	268.5
6a	127.9	53.6	401.7	312	0.98	318.3

Table 3. Installed power and the corresponding energy indicators for the interior zone and nighttime stage of the examined tunnels (the luminaires of the interior zone were installed along the full length of the tunnel).

Tunnel	Installed Power (kW)	Power Density (W/m^2)	kW/km	Number of Luminaires	Luminaire/m	Length (m)
1a	30.2	5.7	43.1	160	0.23	702.1
1b	24.2	4.9	36.8	133	0.20	656.4
2a	144.5	7.8	58.4	744	0.30	2474.7
2b	129.4	7.0	52.6	630	0.26	2457.6
3a	12.2	6.4	48.3	54	0.21	253.4
3b	12.2	6.4	48.3	54	0.21	253.4
4a	20.1	9.1	68.4	82	0.28	294.0
4b	15.5	7.2	54.0	64	0.22	286.7
5a	3.2	1.6	11.9	26	0.10	272.4
5b	3.1	1.5	11.2	24	0.09	273.0
6a	13.7	3.6	26.8	80	0.16	510.3

2.2. *Luminance Calculations (L20)*

As the proposed methodology compares the existing threshold luminance Lth, with the new Lth′, the luminance L20 at the access zone has to be calculated. The L20 value can be obtained either from estimation [31] or by using a combination of a photo of the tunnel entrance and corresponding calculations according to the standards [31]. More specifically, the photograph should be taken from a point at a distance equal to the stopping distance from the tunnel portal in the middle of the specific motorway or traffic lane with the road closed off [58]. The evaluation of L20 was obtained using the photographs, one for each of the eleven tunnels, presented in Figure 3 with the aid of the equation (1):

$$L20 = \gamma \cdot L_C + \rho \cdot L_R + \Sigma\,(\varepsilon \cdot L_E) \quad (1)$$

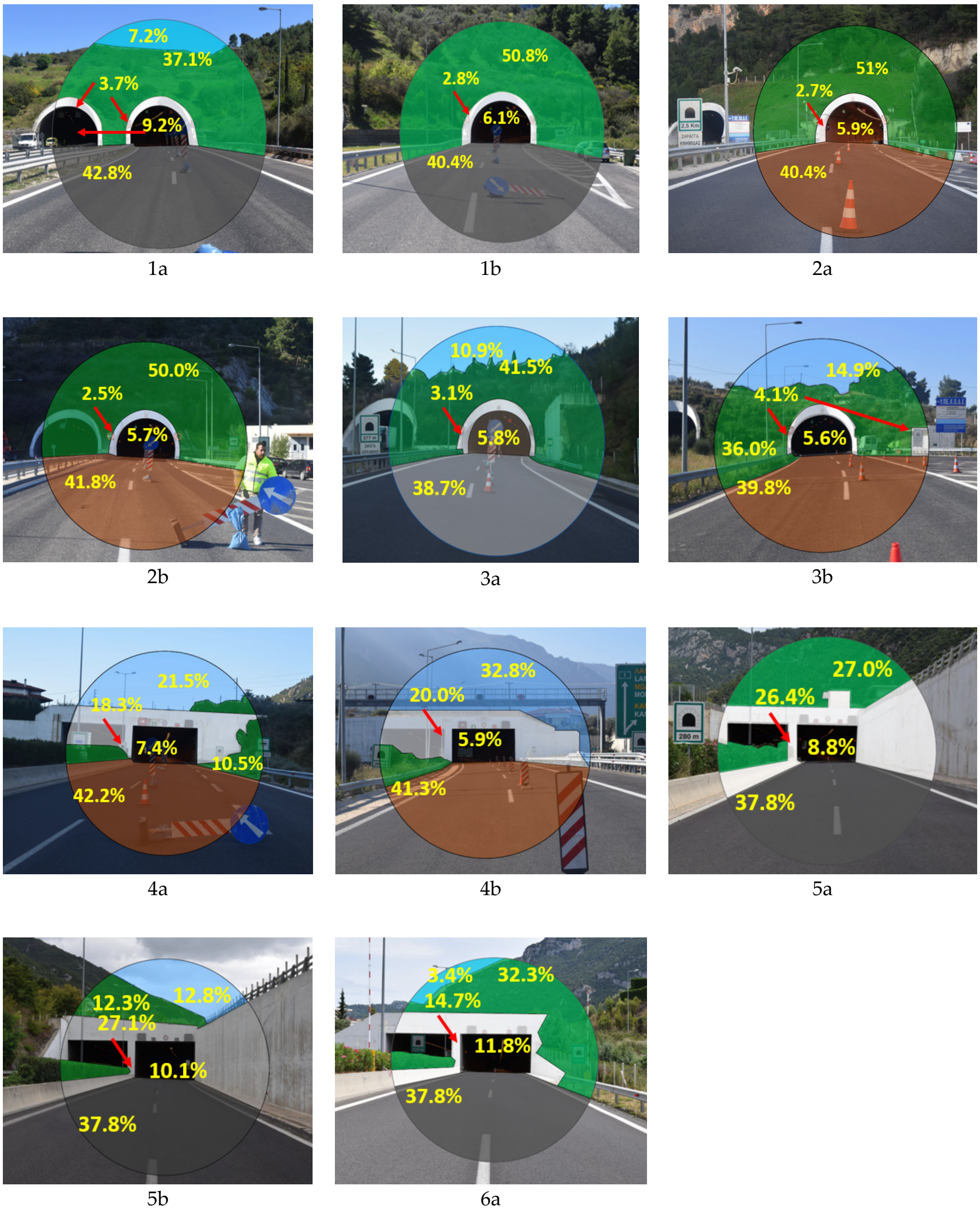

Figure 3. Photographs, taken from a point at a distance equal to the stopping distance from each of the tunnel portals in the middle of the specific motorway, presenting the parts of sky (%), road (%), surroundings (%), and portal (%) used for the calculation of the access luminance L20.

Where: L20 is the access zone luminance, L_C is the sky luminance, γ= (%) of sky, L_R is the road luminance, ρ = (%) of road, L_E is the surrounding luminance and ε = (%) of surroundings.

The parameters used for the calculation of L20 are presented in Table 4 while Table 5 shows the luminance requirement for the new threshold zone Lth′. The k factor was calculated from Table 6 using interpolation. All the tunnels were classified as class 2 for motorized traffic only and medium traffic flow. The new calculated luminance values in each threshold zone are presented in Table 5. The corresponding Lth′ values varied from 26% to 60%, which was lower than the corresponding existing one Lth, a fact meaning that the lighting systems are over-dimensioned for all the tunnels.

Table 4. Corresponding values used in Equation (1) in order to calculate the L20 [31] luminance for all examined tunnels.

Tunnel	1a	1b	2a	2b	3a	3b
Driving direction	East Southeast	South West	East Southeast	West	East Northeast	West
γ (%) of sky	7.2%	0%	0.0%	0%	10.92%	14.9%
Lc (Sky) (kcd/m^2)	13	14	13	12	11	12
ρ (%) of road	42.8%	40.4%	40.4%	41.8%	38.73%	39.4%
L_R (Road) (kcd/m^2)	4.25	4.5	4.25	4	3.75	4
ε (%) of surrounding – vegetation	37.1%	50.8%	51.0%	50.0%	41.46%	36.0%
L_E (Vegetation) (kcd/m^2)	2	2	2	2	2	2
ε (%) of surrounding – buildings	3.7%	2.8%	2.7%	2.5%	3%	4.1%
L_E (Buildings) (kcd/m^2)	5.5	5	5.5	6	6.5	6
ε (%) of surrounding - rock	0.0%	0.0%	0.0%	0.0%	0%	0.0%
L_E (Rock) (kcd/m^2)	1.75	1.5	1.75	2	2.25	2
Tunnel	**4a**	**4b**	**5a**	**5b**	**6a**	**-**
Driving direction	East Northeast	West Southwest	East Southeast	West	East Southeast	-
γ (%) of sky	21.5%	0.0%	0.0%	12.8%	3.4%	-
Lc (Sky) (kcd/m^2) [31]	11	13	13	12	13	-
ρ (%) of road	42.2%	41.3%	37.8%	37.8%	37.8%	-
L_R (Road) (kcd/m^2) [31]	3.75	4.25	4.25	4	4.25	-
ε (%) of surrounding – vegetation	10.5%	32.8%	27.0%	12.3%	32.3%	-
L_E (Vegetation) (kcd/m^2) [31]	2	2	2	2	2	-
ε (%) of surrounding – buildings	18.3%	20.0%	26.4%	27.1%	14.7%	-
L_E (Buildings) (kcd/m^2) [31]	6.5	5.5	5.5	6	5.5	-
ε (%) of surrounding - rock	0.0%	0.0%	0.0%	0.0%	0.0%	-
L_E (Rock) (kcd/m^2) [31]	2.25	1.75	1.75	2	1.75	-

Table 5. Lth′ values using the L20 access luminance and corresponding k factor according the proposed traffic weighted method [31].

Tunnel	L20 (cd/m^2) (1)	k Factor [31] (2)	Lth′ (cd/m^2) (3) = (1) · (2)
1a	3704	0.040	148
1b	2970	0.039	116
2a	2885	0.039	113
2b	2824	0.040	113
3a	3684	0.038	140
3b	4326	0.040	173
4a	5354	0.038	203
4b	3511	0.041	144
5a	3598	0.040	144
5b	4912	0.040	196
6a	3502	0.038	133

Table 6. Recommended values of k factor for different values of stopping distance (SD) for tunnel class 2 (motorized traffic only and medium traffic flow) using the traffic weighed method [31].

Tunnel Class	Stopping Distance SD (m)		
	60	100	160
2	0.03	0.04	0.05

3. Results

3.1. Defining Switching Control

While the incident daylight at the tunnel portal is not stable during the day, there is a need for a switching control based on the daylight levels. Depending on the control of the lighting stage, the energy consumption for the same tunnel can be considerably modified.

3.1.1. Existing Switching (Scenario A)

The existing switching program of the examined tunnel is shown in Table 7. It is based on the signal generated by the L20 luminance meter, which activates the luminaires through the SCADA system. For the existing control switching (Scenario A, Lth) when daylight increases and the L20 value sent to SCADA is larger than the values in Table 7, Stage 1 (S1) is switched on (full light output). If the L20 signal is lower than the corresponding values, then the next lighting stage 2 (S2) is engaged. For example, for Tunnel 1a (Table 7), when L20 value is larger than 1530 cd/m^2, Stage 1 is switched on (full light output, 305 luminaires, 123.8 kW). If the L20 signal is less than 1530 cd/m^2, then the corresponding Stage 2 (S2) is engaged (182 luminaires, 67.3 kW).

3.1.2. Proposed Switching (Scenario B)

For the proposed switching, the threshold luminance (Lth') is different than the threshold luminance Lth of the initial design. The new CIE (Commission Internationale de l'Eclairage or International Commission on Illumination) curves regarding the new Lth' values are presented in Figure 4, and it is evident that the existing stage 2 can satisfy the maximum lighting needs in many cases. This results in greater energy savings, since stage 1 will be set permanently to inactive (Tunnels 2a and 2b, Table 8). In addition, for the next lighting level with the new lower than the existing configuration luminance requirements, S4 is engaged instead of S3. In order to determine the new triggering of the lighting system and the associated L20, a new parameter called Over Lit Triggering Percentage of various circuits (OLTP) is proposed. This percentage is defined as follows:

$$OLTP_{SN} = Lth(SN)/Lth'(S1) \tag{2}$$

Where: Lth (SN) is the Lth of the initial design of the existing tunnel for SN light stage, Lth'(S1) is the luminance requirement for the new threshold zone for S1 stage and SN is the corresponding lighting stage (S1 for N = 1, S2 for N = 2, etc.). Thereafter $OLTP_{SN}$ represents (in percentage) the proposed triggering of each of the existing lighting circuit for SN light stage. Values above 100% meaning that the corresponding switching stage is inactive. This percentage is necessary for the specification of the new triggering of the existed lighting circuits based on the new lower lighting requirements. It is evident that the proposed triggering will now depend on the Lth' and since the existing lighting achieves specific lighting levels due to the existing lighting circuits, their triggering has to be redefined. Hence, the proposed switching control, Scenario B (Table 8) enables all stages at higher values of L20 when compared to the existing configuration. This means that the use of lighting control stages with fewer luminaires and less installed power instead of the existing ones, for the same incident daylight at the portal of the tunnel, can lead to a larger amount of energy savings and lower amounts of CO_2 emissions.

Table 7. Extracted L20 values from Supervisory Control and Data Acquisition (SCADA) system for Scenario A (switching control with existing Lth values) along with the number of luminaires grouped per lighting stage and the corresponding installed power for all the examined tunnels.

Tunnel	Lighting Stage	Light Output	Switching on/off, L20 Luminance Signal for SCADA (cd/m^2)	Power of Luminaires in Operation per Stage (kW)	Power of Luminaires per Stage (kW)	Luminaires in Operation per Stage	Luminaires per Stage
1a	S1	100%	1530	123.8	56.5	305	123
	S2	50%	630	67.3	34.0	182	80
	S3	20%	225	33.4	21.5	102	51
	S4	6%	90	11.8	6.8	51	25
	S5	3%	27	5.0	5.0	26	26
1b	S1	100%	1530	125.0	57.2	305	125
	S2	50%	630	67.7	33.5	180	78
	S3	20%	225	34.3	21.8	102	50
	S4	6%	90	12.4	7.3	52	25
	S5	3%	27	5.2	5.2	27	27
2a	S1	100%	1530	126.3	60.8	306	135
	S2	50%	630	65.5	34.3	171	80
	S3	20%	225	31.2	23.6	91	54
	S4	6%	90	7.6	2.5	37	10
	S5	3%	27	5.2	5.2	27	27
2b	S1	100%	1530	126.5	58.1	310	127
	S2	50%	630	68.5	32.8	183	77
	S3	20%	225	35.6	23.1	106	53
	S4	6%	90	12.5	7.6	53	27
	S5	3%	27	5.0	5.0	26	26
3a	S1	100%	1180	97.0	50.4	222	107
	S2	50%	620	46.6	27.7	115	59
	S3	20%	420	18.9	14.7	56	32
	S4	6%	190	4.2	0.3	24	2
	S5	3%	90	3.9	3.9	22	22
3b	S1	100%	1200	96.8	49.7	221	105
	S2	50%	850	47.0	27.7	116	59
	S3	20%	420	19.4	15.2	57	33
	S4	6%	260	4.2	0.3	24	2
	S5	3%	90	3.9	3.9	22	22
4a	S1	100%	2370	134.1	56.5	290	118
	S2	50%	1100	77.6	47.8	172	100
	S3	20%	600	29.8	21.4	72	45
	S4	6%	200	8.4	5.6	27	12
	S5	3%	90	2.8	2.8	15	15
4b	S1	100%	2000	99.6	49.1	235	105
	S2	50%	1000	50.5	29.5	130	66
	S3	20%	650	20.9	16.0	64	36
	S4	6%	410	4.9	0.7	28	4
	S5	3%	270	4.3	4.3	24	24
5a	S1	100%	1800	110.2	51.6	262	111
	S2	50%	850	58.6	30.4	151	67
	S3	20%	510	28.2	17.6	84	39
	S4	6%	360	10.6	6.7	45	23
	S5	3%	290	4.0	4.0	22	22
5b	S1	100%	1480	147.8	59.3	334	127
	S2	50%	720	88.5	50.8	207	110
	S3	20%	480	37.7	22.9	97	50
	S4	6%	230	14.8	9.2	47	24
	S5	3%	140	5.6	5.6	23	23
6a	S1	100%	1580	127.9	57.1	312	125
	S2	50%	830	70.7	35.2	187	82
	S3	20%	370	35.5	23.1	105	53
	S4	6%	280	12.4	7.3	52	26
	S5	3%	100	5.2	5.2	26	26

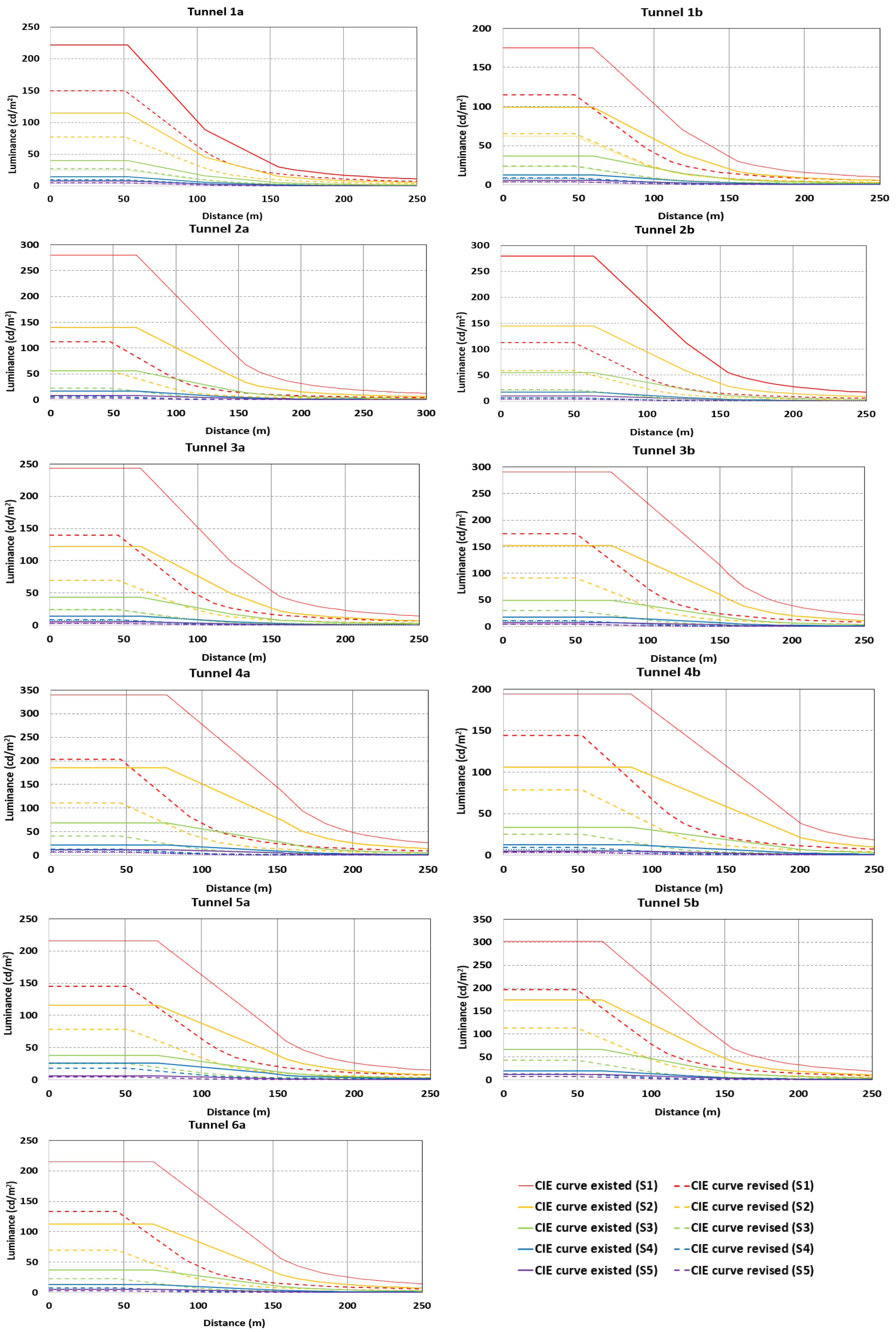

Figure 4. Luminance curves from initial design (existing lighting system) and from the traffic weighted method using the new calculated Lth' values, according to the Commission Internationale de l'Eclairage (CIE) for the examined tunnels.

Table 8. Comparison of the switching control between Scenario A (switching control with existing Lth values) and Scenario B (switching control with new proposed Lth′ values) for all examined tunnels. OLTP = Over Lit Triggering Percentage.

Tun.	Stage	Lth (cd/m^2)	Lth′ from Revised CIE Curve (cd/m^2)	OLTP due to New Luminance Demand, (%)	Light Output Levels for Existing Switching	L20 Triggering Levels for SCADA (cd/m^2)	Light Output Levels for Proposed Switching	New L20 Triggering Levels for SCADA (cd/m^2)
1a	S1	222	148	150%	50%	1530	75%	2780
	S2	111	74	75%	20%	630	30%	1112
	S3	44	30	30%	6%	225	9%	334
	S4	13	9	9%	3%	90	5%	167
	S5	7	4	5%	0%	27	0%	0
1b	S1	175	116	151%	50%	1530	75%	2238
	S2	87	58	75%	20%	630	30%	895
	S3	35	23	30%	6%	225	9%	269
	S4	10	7	9%	3%	90	5%	134
	S5	5	3	5%	0%	27	0%	0
2a	S1	280	113	249%	50%	1530	No use	No use
	S2	140	56	124%	20%	630	50%	1436
	S3	56	23	50%	6%	225	15%	431
	S4	17	7	15%	3%	90	7%	215
	S5	8	3	7%	0%	27	0%	0
2b	S1	280	113	248%	50%	1530	No use	No use
	S2	140	57	124%	20%	630	50%	1400
	S3	56	23	50%	6%	225	15%	420
	S4	17	7	15%	3%	90	7%	210
	S5	8	3	7%	0%	27	0%	0
3a	S1	244	140	174%	50%	1180	87%	3209
	S2	122	70	87%	20%	620	35%	1416
	S3	49	25	35%	6%	420	10%	425
	S4	15	8	10%	3%	190	5%	212
	S5	7	4	5%	0%	90	0%	0
3b	S1	290	173	168%	50%	1200	84%	3626
	S2	145	82	88%	20%	850	34%	1451
	S3	58	33	29%	6%	420	10%	435
	S4	17	10	11%	3%	260	5%	218
	S5	9	5	4%	0%	90	0%	0
4a	S1	340	203	167%	50%	2370	84%	4476
	S2	170	102	84%	20%	1100	33%	1791
	S3	68	41	33%	6%	600	10%	537
	S4	20	12	10%	3%	200	5%	269
	S5	10	6	5%	0%	90	0%	0
4b	S1	194	144	135%	50%	2000	67%	2366
	S2	97	72	67%	20%	1000	27%	947
	S3	39	29	27%	6%	650	8%	284
	S4	12	9	8%	3%	410	4%	142
	S5	6	4	4%	0%	270	0%	0
5a	S1	216	144	150%	50%	1800	75%	2695
	S2	108	72	75%	20%	850	30%	1078
	S3	43	29	30%	6%	510	9%	323
	S4	13	9	9%	3%	360	4%	151
	S5	6	4	4%	0%	290	0%	0
5b	S1	303	197	154%	50%	1480	77%	3787
	S2	152	98	77%	20%	720	31%	1515
	S3	61	39	31%	6%	480	9%	454
	S4	18	12	9%	3%	230	6%	296
	S5	12	8	6%	0%	140	0%	0
6a	S1	215	133	161%	50%	1580	81%	2826
	S2	107	57	81%	20%	830	32%	1131
	S3	43	23	32%	6%	370	10%	339
	S4	13	7	10%	3%	280	5%	170
	S5	6	3	5%	0%	100	0%	0

3.2. Use of LED Luminaires (Scenarios C1, D1, C2, and D2)

In addition, four scenarios were examined where the existing lighting system for each tunnel was retrofitted with LED luminaires (C: 10% step control dimming and D: continuous dimming) using both the existing lighting requirements Lth and the new calculated Lth′ (C1 and D1 for Lth and C2 and D2 for Lth′). Tables 9 and 10 present the number of LED luminaires needed and the corresponding installed power for all scenarios. The data were extracted with the use of the Relux Tunnel light simulation tool [72]. Furthermore, the power density indicator for the entrance zone of the tunnel was calculated as the ratio of its installed power to the area that is defined by the length of the entrance zone of each tunnel and the width of both lanes of the road (7.5 m).

Table 9. Number of LED luminaires needed and the corresponding installed power and the energy indicators for the entrance zone of the examined tunnels for existing Lth luminance requirement.

Tunnel	Installed Power (kW)	Power Density (W/m^2)	kW/km	Number of Luminaires	Luminaire/m	Length (m)
1a	78.8	33.8	253.6	207	0.67	310.7
1b	60.5	26.2	196.5	165	0.54	308.1
2a	64.3	27.5	206.1	175	0.56	312.0
2b	61.8	26.4	198.0	168	0.54	312.0
3a	72.3	38.2	286.8	186	0.74	252.0
3b	78.3	41.6	312.3	196	0.78	250.7
4a	72.2	34.3	257.0	190	0.68	280.9
4b	68.4	31.8	238.5	179	0.62	286.7
5a	66.3	32.4	243.2	171	0.63	272.4
5b	77.1	38.3	287.0	195	0.73	268.5
6a	66.4	27.8	208.7	186	0.58	318.3

Table 10. Number of LED luminaires needed and the corresponding installed power and the energy indicators for the entrance zone of the examined tunnels for the new calculated Lth′ luminance requirement.

Tunnel	Installed Power (kW)	Power Density (W/m^2)	kW/km	Number of Luminaires	Luminaire/m	Length (m)
1a	31.3	13.4	100.9	124	0.40	310.7
1b	22.9	9.9	74.3	94	0.31	308.1
2a	22.5	9.6	72.0	91	0.29	312.0
2b	23.2	9.9	74.4	96	0.31	312.0
3a	26.9	14.2	106.8	104	0.41	252.0
3b	36.9	19.6	147.1	136	0.54	250.7
4a	34.8	16.5	124.0	133	0.47	280.9
4b	28.2	13.1	98.5	110	0.38	286.7
5a	26.7	13.1	98.0	104	0.38	272.4
5b	36.6	18.2	136.3	137	0.51	268.5
6a	23.7	9.9	74.5	98	0.31	318.3

3.3. Energy Calculations

For the corresponding energy calculations, eight days, from 5 February, 2020 to 13 February, 2020, were considered. The readings of the input signal of the lighting system and the switching control were taken from SCADA, as luminance values per minute. Six scenarios were used:

- Scenario A: Switching control with existing Lth values.
- Scenario B: Switching control with newly calculated Lth′ values.
- Scenario C1: LED Retrofit 10% step control dimming (Lth).
- Scenario C2: LED Retrofit 10% step control dimming (Lth′).
- Scenario D1: LED Retrofit continuous dimming (Lth).
- Scenario D2: LED Retrofit continuous dimming (Lth′).

The L20 signals, for each of the eleven tunnels, are presented in Figures 5 and 6. Table 11 presents the analytic energy calculations for Scenarios A and B. For each scenario the cumulative energy consumption was separately calculated for each lighting stage. It is evident that by minimizing the working hours of lighting stage S1 (maximum light output) the energy saving is maximized. Table 12 presents the total energy consumption for each of the six examined scenarios and their corresponding energy savings.

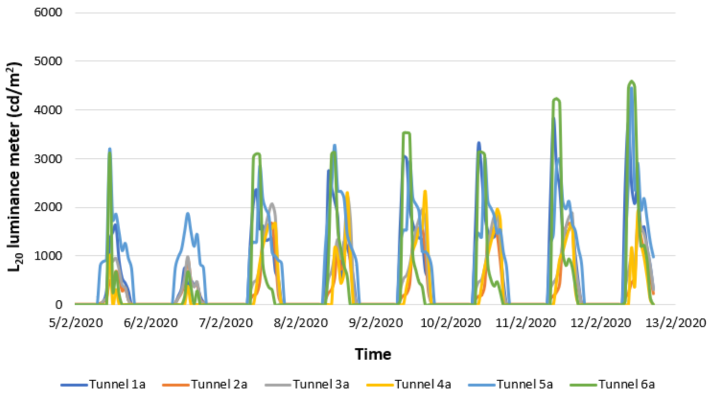

Figure 5. Signal from SCADA due to daylight variation (eight days) for the examined tunnels in the lanes leading to Athens (Tunnels 1a, 2a, 3a, 4a, 5a, and 6a).

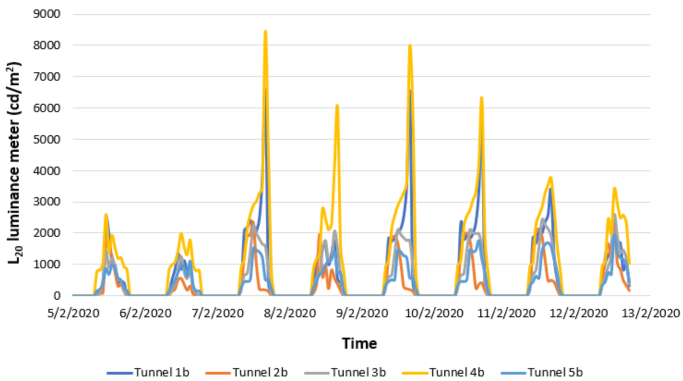

Figure 6. Signal from SCADA due to daylight variation (eight days) for the examined tunnels in the lanes leading to Lamia (Tunnels 1b, 2b, 3b, 4b, and 5b).

Table 11. Comparison of the energy consumption (kWh) between the switching scenarios A and B for the period from 5 February, 2020 to 13 February, 2020.

Lighting Stage	Energy Consumption (kWh)							
	Existing Switching	Proposed Switching	Existing Switching	Proposed Switching	Existing Switching	Proposed Switching	Existing Switching	Proposed Switching
Tunnel	**1a**	**1a**	**1b**	**1b**	**2a**	**2a**	**2b**	**2b**
S1	4333	743	6000	2500	1389	0	2404	0
S2	2221	3432	1286	2843	1769	786	1370	1507
S3	568	835	720	823	842	1123	1104	926
S4	35	71	25	37	160	137	225	300
S5	30	25	21	26	21	125	15	95
Total	7187	5106	8052	6230	4181	2171	5117	2828
Tunnel	**3a**	**3a**	**3b**	**3b**	**4a**	**4a**	**4b**	**4b**
S1	2910	0	4259	0	0	0	5080	4183
S2	1025	1072	423	1457	1940	310	1364	1313
S3	246	794	446	873	447	1162	481	690
S4	76	76	29	42	109	76	0	0
S5	20	27	23	35	6	8	0	0
Total	4276	1969	5181	2407	2502	1557	6924	6186
Tunnel	**5a**	**5a**	**5b**	**5b**	**6a**	**6a**	**-**	**-**
S1	3857	992	296	0	4604	2942	-	-
S2	3282	3868	1416	0	919	1485	-	-
S3	226	677	302	1056	426	604	-	-
S4	0	0	178	104	0	37	-	-
S5	0	0	50	67	21	16	-	-
Total	7364	5536	2241	1226	5970	5083	-	-

Table 12. Total energy consumption, annual CO_2 emission (using the emission factor 1058.95 $kgCO_2$/MWh e) per electricity mix of Greece [73,74]) and energy savings comparisons between the examined scenarios for the period from 5 February, 2020 to 13 February, 2020.

Scenario	Description	Energy Consumption (kWh)	CO_2 Emission (tn)	Energy Savings (%)		
				Due to New Lth′	Due to LED Luminaires	Total
A	Switching control with existing Lth	59,507	63.0	-	-	-
B	Switching control with newly calculated Lth′	40,784	43.2	31.5%	-	31.5%
C1	LED Retrofit 10% step control dimming (Lth)	23,792	25.2	-	56.9%	56.9%
D1	LED Retrofit continuous dimming (Lth)	22,659	24.0	-	61.9%	61.9%
C2	LED Retrofit 10% step control dimming (Lth′)	9483	10.0	22.9%	56.9%	79.8%
D2	LED Retrofit continuous dimming (Lth′)	9032	9.6	22.9%	61.9%	84.8%

4. Discussion and Conclusions

The total annual electrical and primary energy consumptions of the existing installation (11 tunnels) were 2715 MWh and 7874 MWh correspondingly (Figure 7). The energy consumption from the examined period (Table 12) was normalized for a year, while the Primary Energy Numeric Indicator (kWh p = 2.9 × kWh e [75]) from Greece was used in order to convert the electrical to primary energy.

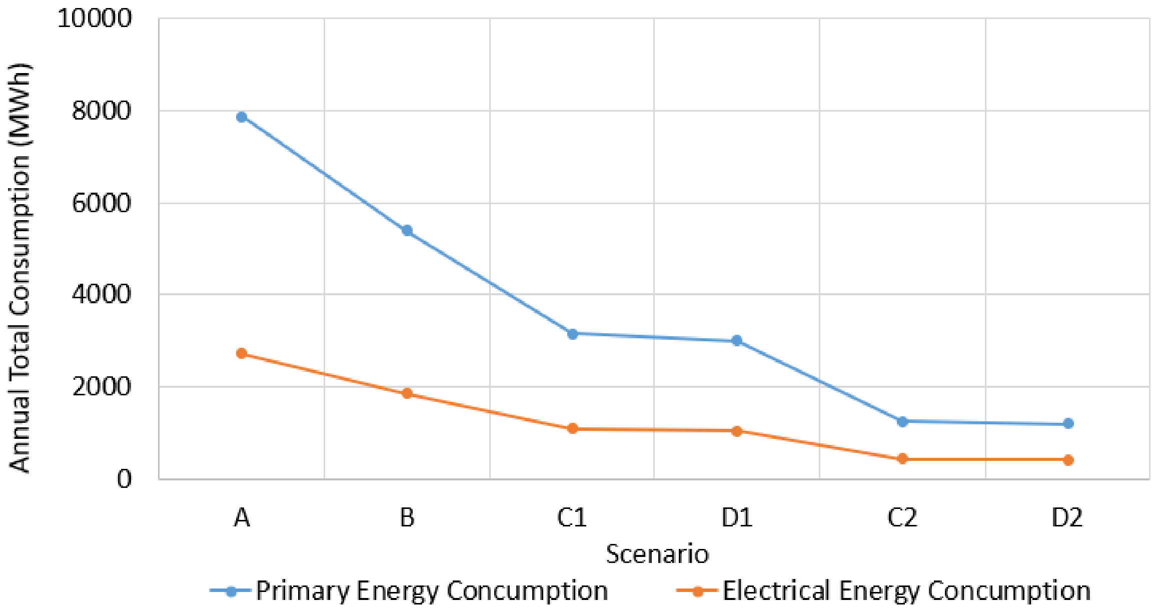

Figure 7. Total annual electrical and primary energy consumption for the examined scenarios.

Using the proposed methodology, the primary energy consumption can be reduced to 5396 MWh (Figure 7) while the corresponding annual CO_2 emission reduction is 904.6 tn. Thus, the energy savings can reach a figure of 31% using the new switching control strategy, according to the calculated Lth′. If combined with the retrofitting of existing luminaires with LED technology, the energy savings can increase and reach 62%. The corresponding difference in energy savings between Scenario B and C2 (31%) could not be viable as the cost of a LED tunnel luminaire, including the labor work for the new installation, is still high. However, using the new Lth′ values (Scenario D, Figure 8) energy savings are 23%, while by retrofitting the existing luminaires with LEDs, additional energy savings of up to 62% can be achieved. Figure 9 presents the annual energy costs together with the initial costs of the LED luminaires versus the annual primary energy consumption per square meter of the entrance zone of the examined tunnels. Each dot represents a case examined while the cases are grouped (different color) according to the scenarios. A price of 1200 euros per luminaire was taken as the initial cost of the LED luminaire, the cost of energy was calculated at 0.15 euros per kWh while the Primary Energy Factor was considered equal to 2.9 (Greece, [75]). The lower primary energy consumption and the cost are, (lower left part of the diagram in Figure 9) the more the beneficial is the action of the examined scenario. It seems that Scenario B (orange dots), represents the most beneficial one.

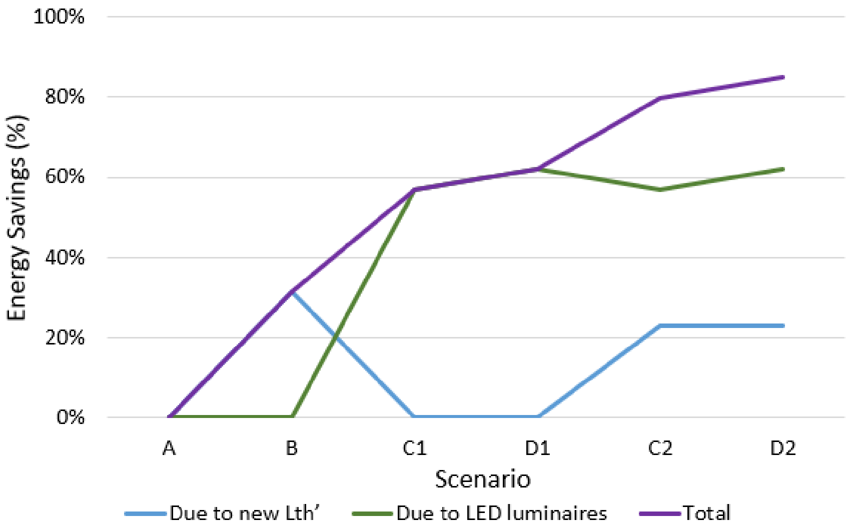

Figure 8. Breakdown of the energy savings due to the new calculated Lth′ values and the retrofit of the existing luminaires with new LED luminaires for each of the examined scenarios.

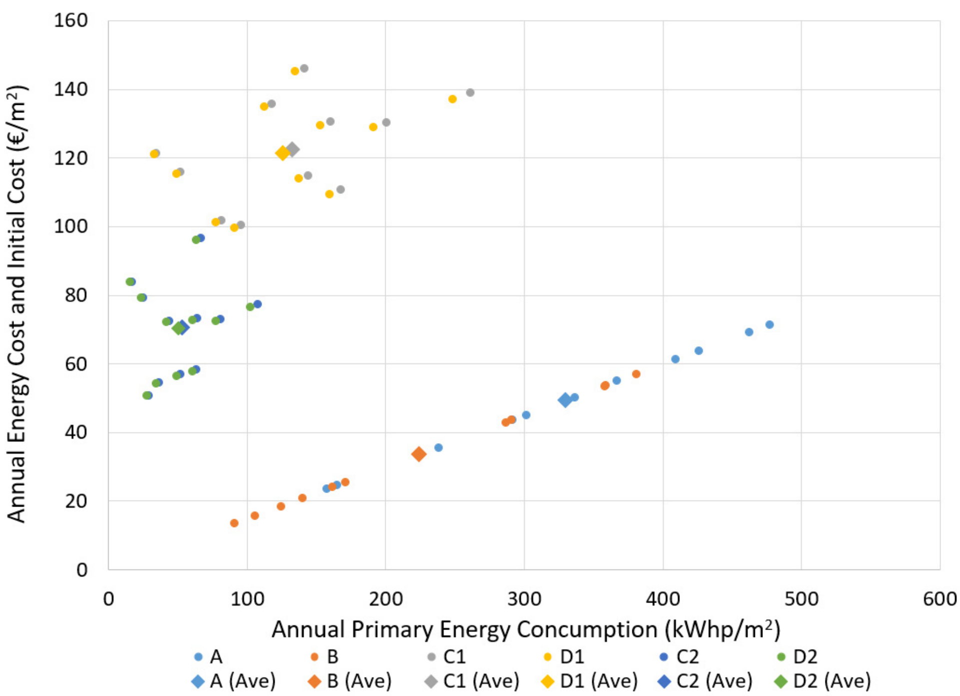

Figure 9. Annual energy cost and initial cost for LED luminaires versus the annual primary energy consumption per square meter of the entrance zone of the examined tunnels (11 tunnels in regards 6 scenarios with the corresponding average values per scenario).

From the aforementioned results, it is evident that over-illumination and oldness of the existing tunnels result in increased and unwanted energy consumption especially in the daytime. A technical committee from the International Commission of Illumination (CIE 4–53 Tunnel Lighting Evolution) for tunnel upgrading has been formed [76] in an effort to minimize energy consumption. In addition, many lighting experts propose various actions such as using daylight control systems and different types of pavement in a similar attempt to reduce energy consumption. The proposed methodology, although simple, is not fully integrated into current energy saving policies. The revision of the Lth values should be a step taken prior to the action of replacing the existing lighting system with LED luminaires. The paper proposes a switching control strategy, which can be a useful tool for lighting designers, road authorities, and lighting experts. This switching control combined with the traffic weighted L20 method as described in CR14380 (Scenario B), can result in significant energy savings at no extra cost. Calculations were performed and energy savings was, on average, 31% varying from 11% to 54% depending on the tunnel. By replacing existing luminaires with LEDs with the existing threshold luminance Lth (Scenarios C1 and C2), energy savings can reach 62% while with the new threshold luminance Lth' (Scenarios D1 and D2), the corresponding values can reach a figure of 85%. Even with the replacement of the existing lighting systems with LEDs, the effect of determining the new threshold luminance Lth' can result in 23% more energy savings (comparing C and D scenarios). Thus, the proposed methodology is suitable for being considered in retrofit actions with LED luminaires. However, this increase in energy savings is accompanied by the additional cost of the 2018 new LED luminaires (scenario C) or of the 1227 luminaires for scenario D, together with a new Supervisory Control and Data Acquisition system, as well as extra installation costs, such as wiring and the corresponding labor cost. In many cases, the extra cost for a new lighting installation compared with the no-cost switching strategy could make the renewal of the installation unsustainable if the cost of the luminaires is high. In addition, the proposed methodology a) is easy to apply with immediate results, b) the calculation of the new L20 values could be necessary in order to evaluate the initial design due to safety reasons, and c) no tender is required for its realization.

For future research, the proposed method could also be combined with traffic detection sensors, as the traffic volume can determine the tunnel class and thus the necessary lighting needs. For example, a tunnel class 3 with high traffic flow, could result in class 2 with medium traffic flow for a time period. As factor k will be defined by lower values, the new Lth' values should determine a new control switching. In general, the energy savings using traffic intensity detector parameters could end up to 50% [77–83]. Furthermore, frequent luminance measurements could enhance the energy savings. Monitoring the real situation of the lighting system, the switching system of SCADA can be fine-tuned, taking into account the lumen maintenance control strategy technique and the actual lighting levels. For this procedure, there are several novel methods for road luminance measurements, where luminance measurements are combined into mobile mapping systems and three-dimensional (3D) measuring [84–89].

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

Factor k	Threshold zone luminance ratio (k) at a point: the ratio between the threshold zone luminance Lth and the access zone luminance L20. Typical values are given by [31]
Lth	Threshold zone luminance, the average road surface luminance of a transverse strip at a given location in the threshold zone of the tunnel (as a function of the measurement grid).
Lth (S1)	Lth (SN) is the Lth of the initial design of the existing tunnel for SN light stage, S_N is the corresponding lighting stage (S1, S2, etc.)
Lth′ (S_N)	Lth′ (S1) is the luminance requirement for the new threshold zone for S1 stage
L20	Average luminance contained in a conical field of view, subtending an angle of 20° with the apex at the position of the eye of an approaching driver and aimed at the left of the tunnel mouth. L20 is assessed from a point at a distance equal to the stopping distance from the tunnel portal at the middle of the relevant carriage-way or traffic lane.
L20 formula: Lc	Typical values of sky luminance depending the driving direction given by [31]
L20 formula: L_R	Typical values of road luminance depending the driving direction given by [31]
L20 formula: L_E	Typical values of surrounding luminance depending the driving direction given by [31]
L20 formula: γ	Percentage of the area of the sky covering the area contributing to the L20 value at the tunnel entrance
L20 formula: ρ	Percentage of the area of the road covering the area contributing to the L20 value at the tunnel entrance
L20 formula: ε	Percentage of the area of the surrounding covering the area contributing to the L20 value at the tunnel entrance
Over Lit Triggering Percentage (OLTP)	Lth (SN)/Lth′ (S1) Where Lth (SN) is the Lth of the initial design of the existing tunnel for SN light stage, Lth′ (S1) is the luminance requirement for the new threshold zone for S1 stage and SN is the corresponding lighting stage (S1 for N=1, S2 for N=2, etc.). Thereafter $OLTPR_{SN}$ represents (in percentage) the new triggering of each of the existing lighting circuit for SN light stage. This percentage is necessary for the specification of the new triggering of the existed lighting circuits based on the new lower lighting requirements. It is evident that the proposed triggering will now depend on the Lth′ and since the existing lighting achieves specific lighting levels due to the existing lighting circuits, their triggering has to be redefined.

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