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Article

Energy Optimization of Road Tunnel Lighting Systems

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Abstract: A road tunnel is an enclosed and covered infrastructure for the vehicular traffic. Its lighting system provides 24 h of artificial sources only, with a higher amount of electric power used during the day. Due to safety reasons, when there is natural lighting outside the tunnel, the lighting levels in the stretches right after the entrance and before the exit must be high, in order to guide the driver's eye towards the middle of the tunnel where the luminance must guarantee safe driving, avoid any over-dimensioning of the lighting systems, and produce energy savings. Such effects can be reached not only through the technological advances in the field of artificial lighting sources with high luminous efficiency, but also through new materials for road paving characterized by a higher reflection coefficient than other ordinary asphalts. This case study examines different technical scenarios, analyzing and comparing possible energy and economic savings. Traditional solutions are thus compared with scenarios suggesting the solutions previously mentioned. Special asphalts are interesting from an economic point of view, whereas the high costs of LED sources nowadays represent an obstacle for their implementation.

Keywords: road tunnel; lighting systems; LED; special asphalts; energy optimization; amortization costs

1. Introduction

Lighting systems are designed to ensure that the vehicular traffic traverses the road tunnel in the most comfortable and safe way possible, aspiring to have the same conditions that characterize the zones preceding and following the tunnel. This case study focuses on the so-called long tunnels; such name derives from the fact that they present a length, between the entrance and exit zones, which is higher than 125 m [1].

During the entire day, the interior zone of the tunnel must have a minimum amount of lighting [2,3] to allow safe driving without overloading energy consumption and management costs. Lighting a tunnel becomes even more onerous when there is high luminance outside the structure. For this reason, the tunnel lighting system consumes more electric power by day, especially during the summer months, with the longest time intervals between dawn and dusk determining higher luminance levels outside the structure due to an apparent higher sun position and clearer skies.

In accordance with the current regulations [4–6], to avoid a decrease of the drivers' visual perception while passing from the outside (highly illuminated due to solar radiation) through to the inside of the tunnel with a different lighting level, it is necessary to realize a particularly illuminated zone in the tunnel (threshold zone + transition zone, complying with CIE 88 [2]) which introduces the drivers to the new conditions of visual perception they will find inside the tunnel.

The length of such zone (threshold zone and transition zone) must ensure the driver an amount of time to adapt their eyes to the different luminance levels they find outside (high luminance levels) and inside (low luminance levels) the tunnel in a way that possible obstacles can be detected. The length will be directly proportional to the luminance value of the entrance zone. In these zones, the eye of the driver must adapt while passing from photopic to mesopic or scotopic conditions; this time interval is very long in humans. This fact requires high lighting levels in this section of the tunnel. Moreover, those drivers who are approaching, from the outside, the tunnel entrance characterized by a low lighting level, are affected by the so called "black hole effect". That is, they perceive the first section of the tunnel as a very dark zone as soon as they enter and they are not able to identify possible obstacles on the road in the first zone of the tunnel.

The final stretch, immediately before the exit, is characterized by contrasting requirements: the intensity of the artificial lighting must be progressive to guarantee the eye to adapt to the high levels of the outside luminance. While trying to find a solution to this kind of problem, some researches exploit solar energy to light the beginning and end of the tunnel [7]. Conversely, some other studies [8,9] suggest the implementation of solar energy to light the beginning and end of the tunnel [7], while other studies [8,9] suggest the exertion of pergols and diffusers materials in the zones preceding and following the tunnel.

Standards require a luminance level (expressed in cd/m^2) of a few units in the interior zone of tunnels, while in the threshold, transition, and exit zones it can reach values of 102 cd/m^2. To comply with the required lighting demand (both at the beginning and end of the tunnel) with artificial lighting systems, it is necessary to use a significant amount of electric power. This implies that the lighting system must be formed by a high number of light sources, presenting high costs due to the construction of the structure and energy management of the road tunnel [10].

For the optimization of the financial management of a road tunnel, it is necessary to invest in new technologies that guarantee an economic return during the lifetime of the systems. Those technologies, examined here, are not prototypes or at an embryonic stage, but are developed technologies already on the market. Two different strategies can be assumed. The most obvious one is to execute a direct intervention on lighting systems, substituting (where possible) the lamps now used (high pressure sodium lamps) with the latest highly efficient light sources such as LED lamps with an extended service life (in this way the light source needs to be changed less frequently than traditional artificial light sources and ordinary maintenance costs will decrease) [11,12]. Indeed, they permit savings in terms of electricity and maintenance, with respect to other light sources. Conversely, another solution concerns the road surface, with the idea being to replace the asphalt commonly used with a type of special asphalt (already on the market, but with low amounts of production). Even though this asphalt is more expensive, it is characterized by higher reflection coefficients of the visible radiation; this feature ensures the same lighting results on the usable surfaces while using systems with a lower luminous flux and, therefore, consuming less electric power.

2. The Case Study

The "Genzano" tunnel, on the A24 highway right in the middle of the Italian peninsula, is the object of this study to analyze how choosing the lighting devices and a certain type of asphalt affect the financial management of the tunnel. In particular, it was taken into consideration the entrance of the tunnel from Rome directed to L'Aquila. The tunnel (Figure 1) is a double-arch, lacking any longitudinal slope, whose length is of 1.5 km.

Figure 1. Entrance to the tunnel.

It is characterized by a medium-high traffic flow [13] and the maximum speed limit, for the vehicles, is 130 km/h. Standards [5], for this type of road, in case of need, require a maximum stopping distance of 163 m. Solar radiation outside the tunnel depends on its geographical position and the geographical coordinates of the site are: 42°20′38.45N for the latitude and 13°19′06.74E for the longitude. Those regulations concerning the atmospheric luminance, hence the section of the sky that the driver sees when he is about to enter the gallery (thanks to the polar Diagram developed by Adrian (Figure 2) [14,15]), according to the maximum estimated speed of the vehicle, the typology of the artificial lighting system currently used, and the luminance of the vehicle dashboard and windshield, allows one to make an estimation of the debilitating luminance affecting the visual perception while producing glare phenomena.

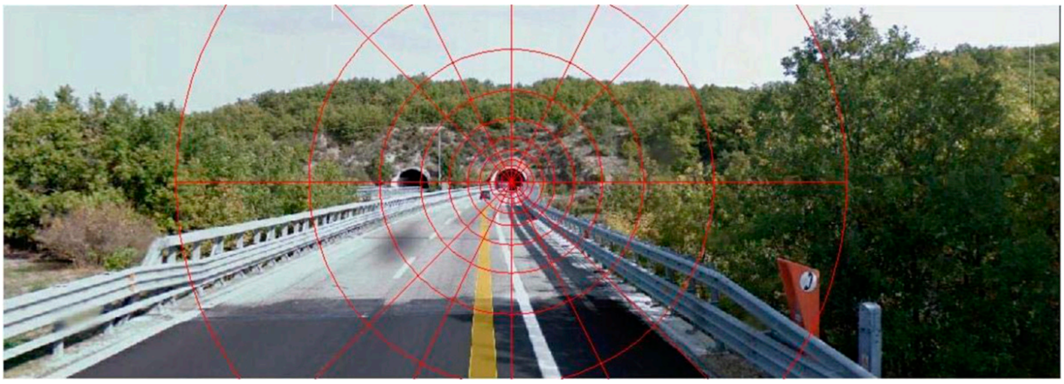

Figure 2. Adrian diagram applied to the tunnel entrance.

In such circumstances the human eye cannot see an obstacle correctly on the highway, thus endangering the road safety. A well-planned lighting system must properly strengthen the artificial lighting in the tunnel entrance to avoid dangerous situations, whatever the solar luminance level outside the tunnel. At first, this luminance must diminish progressively during the stretch that follows, that is the threshold and transition zone, and then balance with the lighting required in the interior zone of the tunnel.

By applying the principles of the regulations to this case study (a tunnel with a length of 1.5 km) in the daytime, the minimum luminance estimated by the plan in the entrance (whose length is about 165 m) is 148 cd/m^2; it must diminish progressively in the threshold and transition zone (whose total length is about 515 m) until reaching a value of 3 cd/m^2 in the interior zone (whose length is about 675 m), then increase again in the exit zone (whose length is about 145 m), reaching a value of 15 cd/m^2 (Figure 3).

During the night, all of the problems related to the daylight and the adaptation of the drivers' eye to the different levels of exterior luminance and its solar radiation disappear. For this reason the luminance in the tunnel must decrease until reaching 1 cd/m^2. This is important to save energy and avoid the opposite problem: the driver passes from the dark of the outside to the artificial light of the tunnel and, while entering, he must not be dazzled by a light which is too strong [16,17]. In order to modulate both diurnal and nocturnal luminance values, the system must have sources with an uninterrupted service able to guarantee permanent lighting and sources able to reinforce the lighting used by day only.

In accordance with the lighting standards imposed by the regulations, thanks to the Dialux light planning software, four different planning scenes were examined. Table 1 shows their characteristics. For each case the number of light sources necessary to guarantee the proper luminance levels in every stretch of the gallery was determined (Figure 3).

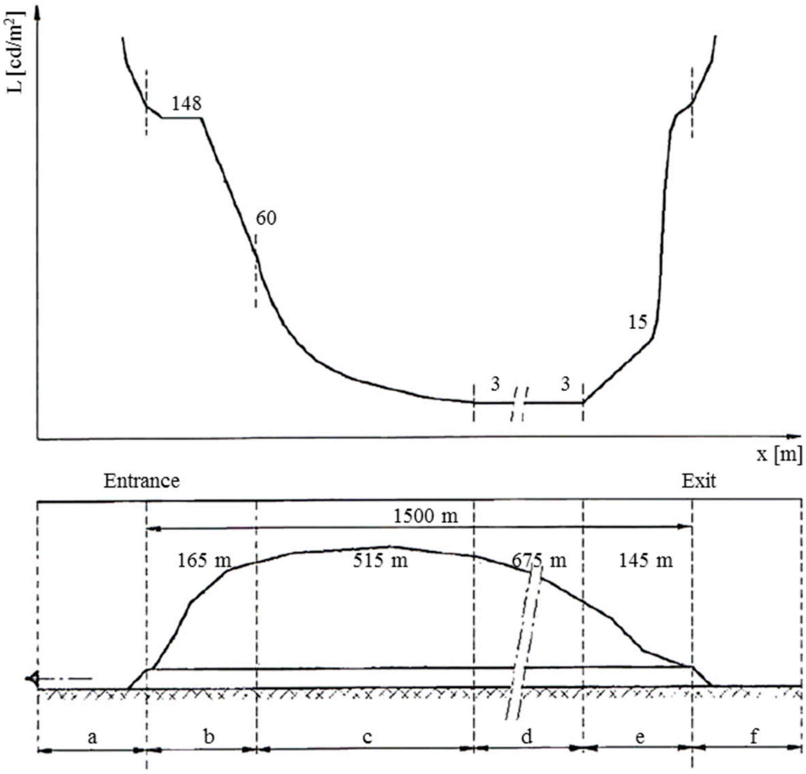

Figure 3. Luminances based on the plan and lengths of the tunnel zones that must be lighted in different ways (a: access zone; b: threshold zone; c: transition zone; d: interior zone; e: exit zone; f: parting zone [2]).

Table 1. Scenes examined.

	Lighting System		Asphalt Type	
	HPS	**HPS + LED**	**Traditional**	**Special**
Case 1	X		X	
Case 2		X	X	
Case 3	X			X
Case 4		X		X

Case 1 presents a more traditional configuration: it suggests the implementation of a lighting system with high-pressure sodium (HPS) lamps only. This type of technology is the one with the highest number of installations in road tunnel lighting systems similar to the one examined here. The case study is characterized by a symmetrical geometric lighting device; that means it presents an equal emission in both directions (the one in which the driver is traveling and the opposite one). In this way, if the tunnel manager, due to accidental reasons, decides to reverse the vehicle traffic, the lighting system is always adequate. The road paving examined here is a traditional asphalt formed by a bituminous mix with a reflection coefficient of the luminous radiation of 7%.

Case 2 is different from Case 1 due to the substitution, where possible, of HPS lamps with LED lights. This kind of light source can be used especially in the interior zone where low levels of lighting are required. The strong luminous flux, for the light reinforcement (in particular in the entrance zone and in the final stretch before the exit zone), prevents a total substitution of HPS lights with LED lamps. LED lamps, nowadays, still present specific luminous fluxes which are not strong enough. This is the reason why the light must be reinforced in those zones with both HPS and LED lamps. HPS lamps provide light in the daytime and will be off during the night (since, by night, the level of required lighting is lower) and substituted by LED lamps. The implementation of LED sources wants to result in a significant financial saving, regardless of their luminous efficiency (right now the world of technology reports that LED lamps have luminous efficiency values which are close to those characterizing HPS lamps), but rather result in maintenance savings due to their substitution. These solid-state lighting sources have a longer service life than HPS lamps. Table 2 shows the main technical features of both sources used. The difference between the power supply of lamps and a grid-connected power system, vital for the right functioning of the whole lighting device, is provoked by the consumption of the electronic supply. LED lamps are characterized by a light source incorporated on the printed circuit board supplying them and this does not allow the substitution of the transmitting element only. In case of damage the whole electronic device must be substituted.

Table 2. Lighting properties of the light sources used.

Type	Luminous Flux (lm)	Power (W)	Connected Power (W)	Service Life (h)	Cost (€) Device	Cost (€) Lamp
HPS (1)	28,600	1 × 400	470.6	5000 ÷ 12,000	361.1	41.2
HPS (2)	51,000	2 × 400	880.0	5000 ÷ 12,000	485.0	41.2
LED	21,000	90	188.0	50,000 ÷ 90,000	723.8	-

Case 3 is different from Case 1 because of the exertion of a special asphalt with a high reflection coefficient. Particular attention was paid to the technical features of Kromatis road surfaces formed by a special binder made of hydrocarbon resin with low asphaltene content. It is characterized by a yellow light color. In order to have this type of color, this special asphalt can present (with a maximum of 2%) the following pigments: (i) iron oxide; (ii) chrome oxide; (iii) yellow 3R; (iv) blue 100. The average reflection coefficient, in the range of visible radiations, is of 15%. This asphalt, tested through the method ASTM D1500 [18] (which allows to determine the color of the petroleum products according to a standardized scale) and lighted by an artificial light source with a color temperature of 2750 K, has an index ≤7. According to such regulations the corresponding chromaticity coordinates are those reported in Table 3.

Table 3. ASTM D1500-03: color scale for petroleum products.

ASTM Color	Chromaticity Coordinates * (RGB USC System) [19]			Luminous Transmittance (CIE Standard Source C)
	Red	Green	Blue	T_W
7.0	0.877	0.123	0.000	0.016 ± 0.004

* Tolerances on the chromaticity coordinates are ±0.006.

Different from traditional asphalts, its production is more complex and expensive; hence, it results in higher production costs. Lighting performances being the same, its use can reduce the power required by the lighting systems, thus decreasing installation and energy costs caused by electric consumption. Moreover, this type of asphalt helps drivers to see possible obstacles on the road more easily.

Case 4 combines a lighting system formed by HPS and LED lamps with a road surface characterized by a special asphalt. The result is a high investment in new technologies, but the solutions suggested should lead to a lower number of lamps and a decrease in management costs.

Case 1 will be taken as a point of reference to compare the other scenes and evaluate their good qualities.

In order to compare all scenes they must guarantee equal lighting performances. The regulations suggest higher luminance values (about 20%) than the minimum values recommended without causing a waste of electric power.

3. Lighting Results

The lighting planning was performed with Dialux Evo [20] software by reproducing the examined tunnel in 3D and placing a proper number of artificial light sources in every zone of the tunnel (Figure 3) in a way the luminance values corresponded to those suggested by the regulations. Figure 4 shows the trends of these values: the dotted curve represents the minimum values required by the regulations to ensure a proper lighting during the day in the tunnel, whereas the continuous curve shows all those values estimated while planning the four scenes examined.

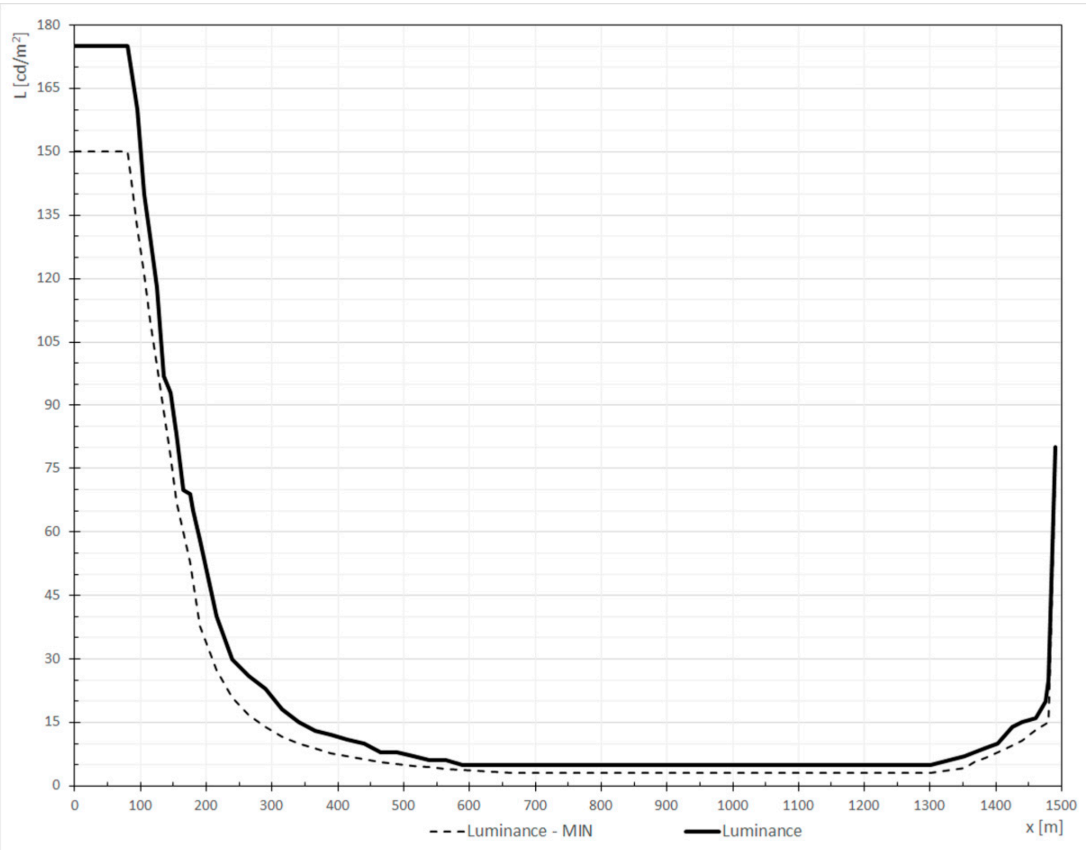

Figure 4. Luminances: minimum limit, in accordance with standards and lighting planning.

The lighting measures were estimated on calculus surface areas placed in the tunnel at regular intervals. Longitudinal luminance values were calculated on calculus surface areas placed in the interior zone of the tunnel, each with a distance of 20 m from one another. In addition to the luminance, in order to obtain a uniform distribution of lighting in every orthogonal zone in the road direction, the ratio between minimum and average luminance (diagonally, with respect to the roadway) was maintained higher than 0.7. For every scene assumed, it was possible to make an estimation of the numbers of artificial light sources necessary to satisfy the lighting requirements.

While observing Figure 5 it can be noticed how, in the daytime and in accordance with the regulations about road safety, it was necessary to use a very high number of lamps in the threshold zone [21,22]. The sources were installed on five parallel rows. The number of lamps decreases in the transition zone until reaching a single-row disposition in the interior zone and then increase again in the exit zone.

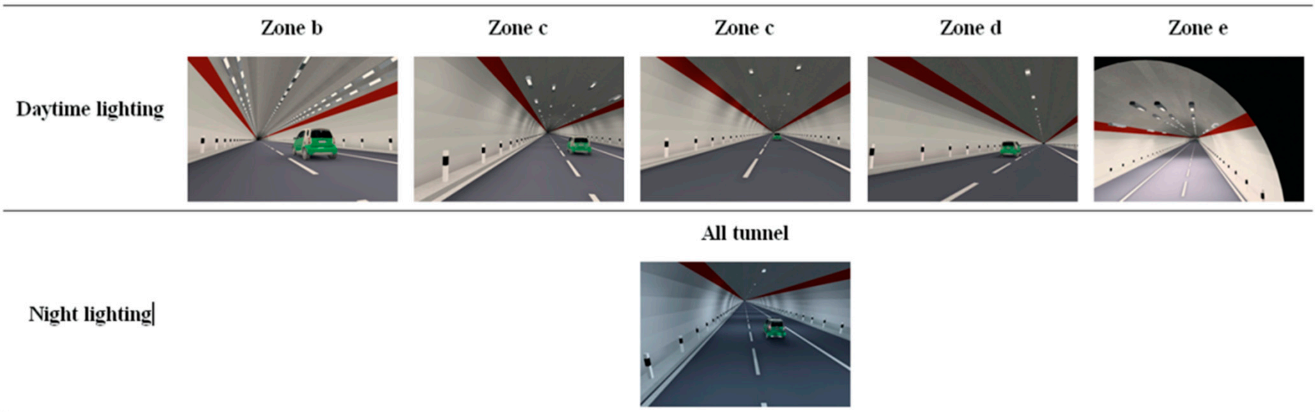

Figure 5. Render of different tunnel zones lighted both in the daytime and nighttime. The transition zone, "c", (which is visible in two different pictures) presents a number of lights diminishing progressively to wire up with the luminous conditions required by the threshold zone, "b", and the interior zone, "d".

Table 4 shows the number of those light sources, divided according to their typology, used by day. It should be noticed how in Scenes 2 and 4, thanks to the light color of the special pavement, the number of luminous devices required is lower than those necessary to Scenes 1 and 3.

Table 4. Number of light sources (divided by typology) turned on in the daytime in all the scenes examined.

Daytime	Zone											
	Threshold			Transition			Interior			Exit		
Case	HPS		LED	HPS		LED	HPS		LED	HPS		LED
	(1)	(2)		(1)	(2)		(1)	(2)		(1)	(2)	
1	356	-	-	58	200	-	-	128	-	21	66	-
2	356	-	-	58	178	35	-	-	191	21	24	24
3	169	15	-	-	172	-	-	45	-	21	55	-
4	184	-	-	-	159	26	-	-	129	21	16	39

Since in the nighttime the reinforcement lighting operating in the daytime is not necessary, it will be turned off to save energy and, consequently, the light sources turned on will be distributed uniformly in the entire tunnel. In Scenes 1 and 3 800 W HPS lamps are turned off, while only a minimum number of 400 W HPS lamps will be kept operative. Scenes 2 and 4 are characterized by LED lights in the interior zone and in the entrance and exit zones: in this way the result will be an optimization of energy consumptions and maintenance reduction. Table 5 shows the number of lights turned on during the night.

Table 5. Number of operating light sources during the night in all the scenes examined.

Nighttime	EntireTunnel	
	HPS	LED
Case	(1)	90 W
1	132	-
2	-	250
3	100	-
4	-	194

4. Economic and Energy Analysis

Simulations performed through Dialux EVO helped to determine, for each scene, the number of lights necessary in every zone of the tunnel. Table 2 shows the data that helped to determine the total amount of power installed in each case. Table 6 refers to the daytime, whereas Table 7 to nighttime.

Table 6. Installed power necessary in the daytime in the scenes examined.

Daytime	N° of Ceiling Mount Lights			Installed Power (kW)			
	HPS		LED	HPS		LED	TOT
Case	(1)	(2)		(1)	(2)		
1	394	435	-	185.4	382.8	-	568.2
2	202	435	250	95.1	382.8	47.0	524.9
3	287	190	-	135.1	167.2	-	302.3
4	205	174	194	96.5	153.1	36.5	286.1

Table 7. Installed power necessary in the nighttime in the scenes examined.

Nighttime	Installed Power (kW)	
	HPS	LED
Case	(1)	
1	62.1	-
2	-	47.0
3	47.1	-
4	-	36.5

Case 1, the most traditional one in terms of types of technology used, requires a high-power system. This amount of power will decrease in Case 2 due to the substitution, in the interior zone, of HPS lamps with LED lights. This will result in an increase in the realization costs, but at the same time, during the managing phase of the system, the result will be a reduction of both energy costs and those expenses caused by the substitution and maintenance of light sources [23–25]. Lighting performances being equal, the decrease of the installed power in Case 3 is significant, due to the implementation of the special asphalt, with installation costs of 5.56 €/m^2 more than a traditional one. In Case 4 the amount of power required is lower due to the substitution, in the interior zone, of HPS lamps with LED lights, though the installation costs are even higher.

EcoCALC [26] was used to make an estimation of the good qualities, from an economic perspective, of the four scenes examined. It is a software tool able to evaluate the amortization of different system solutions while comparing them to a basic case (in this study it would be Case 1) according to the energy and maintenance savings produced through an investment in alternative technologies. In order to perform the calculation of the amortization of the first major investment costs, with respect to a basic system, the software requires the following information: electric energy cost (furnished with an hourly and weekly variability) with the taxes on the power installed; the number, flux, electric power and prices of the lighting devices and artificial light sources chose to be compared in all the different scenes; hourly costs of maintenance expenses of the lighting system and the spaces examined; the time intervals between the maintenance intervention and realization periods; the dimensions of the space examined; financial data such as interest and inflation rate. With these data, by applying the economic principles on the costs amortizations, [27] the software allows a comparison of the different scenes to perform an economic classification of the most advantageous solution from an economic point of view.

In order to make such comparison it was assumed a return period corresponding to the service life of the tunnel lighting system, about 10 years. This time interval is compatible with the lifespan of LED sources, before the whole luminous device gets substituted. Table 8 shows the data necessary for the financial estimation.

Table 8. Data necessary for the financial estimation of the scenes examined.

Annual fee based on the installed power	0.0125	€/kW
Electricity pricing	0.153	€/kWh
Energy costs evolution	5.00	% yearly
Maintenance hourly wage	28.00	€/h
Maintenance costs for the tunnel repainting	5.00	€/m^2
Maintenance cycle for the tunnel repainting	10	years
Inflation rate	2.50	% yearly
Interest rate	5.65	% yearly

The software allows one to take into consideration the costs of the tunnel repainting, as well. A proper maintenance of the inside surfaces characterizing the tunnel (in this case study, this maintenance was assumed to be performed every 5 years) implies periodic high expenses, keeping in mind the extent of the inside surface of a long road tunnel. This expense is useful to maintain a good reflection coefficient of the inside surfaces, which seems to be an affecting element for a good distribution of the luminous fluxes in an enclosed space as a road tunnel.

EcoCALC provides several outputs useful to perform an evaluation of the most advantageous choice, from an economic point of view, of the different system solutions. Table 9 shows the results of the economic analysis.

Table 9. Summary of the economic analysis and comparison of the different scenes examined.

	Case 1	Case 2	Case 3	Case 4	
Total costs of the solution	5,240,990.00	5,176,595.00	3,105,856.00	3,105,856.00	€
Relative total costs	-	98.8	60.3	59.3	%
Total saving	-	64,395.00	2,082,148.00	2,135,134.00	€
Average annual total costs	524,099.00	517,659.00	315,884.00	310,586.00	€/year
Investment expenses ratio *vs.* exertion costs	1:11.2	1:8.6	1:7.6	1:5.0	-
Annual Energy consumptions	2,630,102	2,561,584	1,539,185	1,483,734	kWh/year
Annual Energy saving	-	68,518	1,090,918	1,146,369	kWh/year
Annual energy costs	446,602.00	434,940.00	261,360.00	251,944.00	€/year
Annual energy saving	-	11,663.00	185,242.00	194,658.00	€/year
Annual maintenance costs	23,542.00	19,735.00	12,873.00	4736.00	€/year
Annual maintenance saving	-	3806.00	10,669.00	18,805.00	€/year
Annual exertion costs	470,144.00	454,675.00	274,233.00	256,681.00	€/year
Annual exertion costs saving	-	15,469.00	195,911.00	213,463.00	€/year

5. Discussion

Case 1 reports the highest total expenses, though it is not the solution with the highest installation costs (Figure 6). At the end of the time interval examined for the costs amortization (10 years) energy and maintenance expenses make this solution the least advantageous from an economic perspective.

Case 2 used, where possible, LED lights. Here installation costs increase 26%, with respect to Case 1 (Figure 6). The luminous flux emanated by the devices that can be found nowadays on the market are characterized by low specific values, due to the fact that LED lamps are luminous sources that still must be improved. This is why a high number of these sources must be used in order to produce high illumination. Such choice is uneconomical, if we consider its current cost. Their installation in a tunnel is possible only in those zones requiring a lower amount of illumination, that is the interior zone. In threshold and exit zones, where there is a necessity for reinforcement lighting, to avoid an excessive number of LED lights, it is necessary to use HPS sources as reinforcement lamps. LED lights, even though they produce financial savings for their lower management costs (3.3% respect to Case 1), are not advantageous with respect to total costs (only 1.2%); this is determined by an increase in installation costs, as LED devices are expensive (even if, requiring less installed power, they allow the use of electrical cables of smaller dimensions [28,29]). This solution, with respect to Case 1, is amortized about seven years later (instead of the 10 years, which is the time interval of the study) coinciding with the service life of the systems before the necessary, significant maintenance occurs.

Case 3, the one with special asphalt, presents interesting financial results. Even though the installation of road pavements (with high reflection coefficients in the visible spectrum) increases installation costs with respect to traditional asphalts, the total costs are lower (14% less than Case 1). The lower number of illumination sources, necessary to fulfill the lighting requirements imposed by the current standards, determines installation savings for what concerns the lighting system in this way, balancing the higher expenses of the road paving. The power installed, with less energy than those cases with traditional asphalt, produces an annual energy savings, allowing the initial investments to amortize quickly. During the time interval examined the amount of the electricity saved is significant, hence the result is a decrease in total costs.

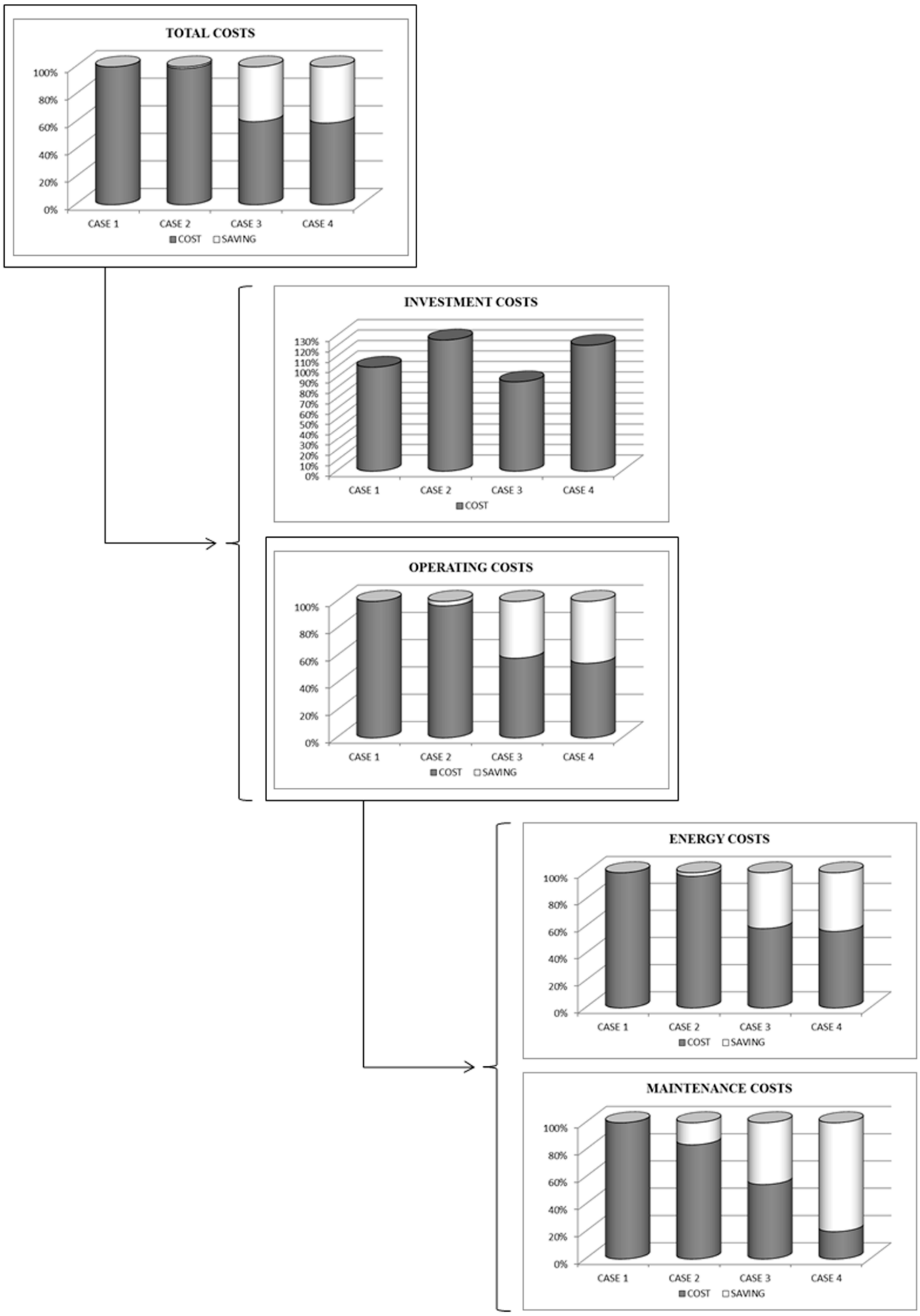

Figure 6. Incidence, in percentage, of the cost items and the financial saving produced in each case, with respect to Case 1. Total costs are determined by installation and management costs. Management costs are determined by energy and maintenance costs.

Case 4 is characterized by both road surface and LED sources installation; due to the special asphalt, as seen in Case 3, it is possible to install a lower number of lamps, with respect to Cases 1 and 2, with the result of producing lower total costs (respectively 40.7% and 39.5%). This solution, if compared to Case 3, reports higher installation costs (21% more than Case 1 and 6% more than Case 3), due to the high installation expenses of LED sources. Their implementation determines both energy and financial savings (because of less maintenance expenses, Figure 6). Case 4 presents, with respect to Case 1, 43.6% of energy saving and 79.9% of maintenance saving. Case 4, if compared to Case 3, determines small energy savings of 2.1%, but, conversely, it presents a maintenance saving of 36.4%. During the time interval examined, Case 4 represents the least expensive solution, even though (with respect to Case 3) it is necessary to wait until the seventh year to recover the installation costs and the final savings obtained are not that substantial.

6. Conclusions

The lighting of road tunnels, defined by the regulations as "long", requires high luminous fluxes (to avoid that the drivers passing from the outside to the inside of the tunnel, and vice versa, are affected by a visual discomfort caused by an insufficient luminance) and this implies a high energy consumption due to the electric power used by the artificial light system. Consumptions are higher, especially during the daytime, in particular in those geographical areas with high solar radiation [30]. In order to let the drivers' eye to adapt while passing from the high luminance levels of the outside to the one characterizing the inside of the tunnel (in the interior zone the luminance must guarantee safe driving but, at the same time, it should not be too energy-consuming) it is necessary to develop a threshold, a transition, and an exit zone with a proper reinforcement lighting. Thus, it is important to have high luminous flux and this is possible with a high number of lighting devices. The case study examined reports that both the electric power necessary and the energy consumption are significant. By night, the energy requirements of the tunnel decrease since the lighting support is not necessary anymore. Companies managing roads presenting long tunnels are always looking for new solutions able to reduce such requirements to optimize both installation and management costs.

Since the 1970s tunnels have been lighted with gas-discharge lamps; sodium lamps in particular. Recently, the technological evolution of these sources led to the implementation of high-pressure sodium lamps (HPS). Usually, the asphalt used for the road surface presents a reflection coefficient in the visible spectrum of 7%. In the past few years new and alternative solutions have been suggested. HPS lamps are supported by LED sources and besides the traditional asphalts it is possible to find on the market special asphalts with a reflection coefficient of 15% as well.

The case study is a 1500 m long road tunnel placed in the middle of the Italian peninsula.

Four different scenes were examined:

- Case 1: traditional asphalt + HPS lamps;
- Case 2: traditional asphalt + HPS & LED lamps;
- Case 3: special asphalt + HPS lamps;
- Case 4: special asphalt + HPS & LED lamps.

Lighting systems, of every scene examined, were planned in accordance with the current standards and in a way to be financially comparable with one another. The regulations expect proper lighting able to fit with the driver safety conditions and let the eye to adapt to the different lighting levels characterizing the inside and outside of the tunnel.

Since the planning shows that LED lamps are characterized by low specific fluxes they are not suitable for the emergency zones in the entrance and at the exit of the tunnel. Due to their luminous efficiency they represent the proper lights for the interior zone and thanks to their longer service life they reduce maintenance expenses.

The asphalt is useful to observe the lighting requirements imposed by the regulations through the exertion of systems characterized by a lower luminous flux than those using both LED lamps and traditional asphalt. The necessity of a lower luminous flux allows the implementation of less artificial sources; hence, a lower amount of installed power.

Considering the amortization period of the expenses equal to the time interval between two extraordinary maintenances (10 years), the case study reports:

- Case 2, with respect to Case 1, produces energy and maintenance savings caused by the low maintenance level of LED sources. Lower management costs repay the higher installation costs in a time interval of about six years.
- Case 3 reports a decrease in installation costs, when compared to Case 1. This result is possible because, though the road paving with special asphalt is of 5.5 €/m^2 more costly than the traditional one, the electric power of the system (thus its realization cost) is 53% of the type necessary in Case 1. Energy savings are significant and total costs, in a time interval of 10 years, are 60%, with respect to Case 1.
- Case 4 presents higher installation costs than Case 1, due to the presence of special asphalt and LED lamps, which are more expensive and increase the system costs respect to Case 3. However these expenses will be amortized in about six months due to the lower energy requirements than Case 1. Case 4, after seven years, is financially more advantageous than Case 3.

The results reported in this case study (in % from a more general point of view) show that the installation in road tunnels of special asphalts, with a high reflection coefficient, though it implies higher investment in installation costs, reduce the amount of power needed in the lighting systems, thus obtaining a fast economic return. If tunnel managers realize how fruitful these asphalts can be (economically speaking) the result will be an increase in the demand, a higher production, and lower costs.

This type of road surface represents an advantage, but the installation of LED sources can add an extra saving due to the lower requirements and reduced maintenance. However LED lights can be even more effective, with respect to energy savings, due to their technological development and their control systems [31,32].

It should not be forgotten that LED technology is the most promising in terms of luminous efficiency, service life, and compactness of the device. Recently, LED devices, useful and effective for lighting wide spaces (as tunnel zones), were introduced on the market; it took a few years to pass from LEDs with a 60 lm/W efficiency to 276 lm/W LEDs (the latter are not on the market yet). In the future years, if this trend continues, the result will be the commercialization of LED sources with a higher efficiency (useful to control consumptions) and devices able to emit higher specific luminous fluxes (useful to control the number of devices required). In this case study, the small amount of specific power prevented their installation in the reinforcement zones (unless there is the necessity of an enormous number of devices to reach lighting levels in accordance with the regulations). Nowadays the high installation costs delay their diffusion even though the distinguishing features are low maintenance costs and high energy performances. In order to make this kind of technology attractive, it is necessary to wait for the fifth-generation LED commercialization with an efficiency of 200–250 lm/W, together with a decrease in production costs.

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Author Contributions

The study was designed by Ferdinando Salata, Iacopo Golasi, Franco Gugliermetti and Andrea de Lieto Vollaro. Simone Bovenzi and Emanuele de Lieto Vollaro carried out the numerical simulations. Francesca Pagliaro and Lucia Cellucci retrieved the data from yearbooks and professional websites and reviewed the literature related to the research. The results were then analysed by Ferdinando Salata, Iacopo Golasi, Simone Bovenzi and Emanuele de Lieto Vollaro. Model design and English corrections were undertaken by Francesca Pagliaro and Lucia Cellucci. Finally, Franco Gugliermetti and Andrea de Lieto Vollaro, the full professors of the research group, supervised the work related to the paper and the execution of its various phases. All authors have read and approved the final manuscript.

Conflicts of Interest

The authors declare no conflicts of interest.

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