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Italian Road Tunnels: Economic and Environmental Effects of an On-Going Project to Reduce Lighting Consumption

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Abstract: Tunnel lighting represents a major cost item for road managers, and particularly in Italy owing to its specific geomorphological and orographic features. In 2018, ANAS, the Italian government-owned road company launched an ambitious program to rehabilitate the lighting systems of more than 700 tunnel tubes across Italy. The Greenlight plan aims to reduce consumption and improve the management of lighting systems while minimizing the impact of works. Outdated high-pressure sodium (HPS) luminaries will be substituted with state-of-the-art light emitting diode (LED) luminaries without modifying the position and the number of the existing luminaires. The project involves an amount of 155 million euros and provides a total return over a less than seven-year period. The first phase of the project involves 147 tubes and is still on-going: 28 GWh (on average 55% of the current consumption) will be saved every year against a 30 million euro investment. More importantly, the economic benefits also have a direct impact on the environment for citizens and safety levels for road users—every year more than 17,000 t of CO_2 eq. and 230 TJ from combustion of fossil fuels will be saved. The lighting quality of the artificial lighting inside the tunnel will be enhanced thanks to better uniformity and the color temperature of the luminaries. The experience presented here could be useful since other road managers may pursue a similar approach in order to balance often-conflicting environmental, economic and safety goals.

Keywords: road tunnel; lighting; LED; road management

1. Introduction

According to the European Commission, improving energy efficiency is a broad term. Improvements in energy efficiency and energy saving are the two key targets [1]. An effective energy efficiency policy could contribute to EU competitiveness and encourage eco-innovation, on the other hand, energy saving is the first option for improving energy efficiency and is undoubtedly the quickest, most cost-effective way to reduce environmental impacts [2]. In the public sector, more efficient lighting can contribute to improving environmental sustainability of our lifestyle [3]. In 2009, 14% of the total electricity consumption in Europe was for lighting, and more than half of this was for public spaces and non-residential applications [4]. In particular, over 70% of existing light sources are based on obsolete technologies that have poor energy performance, and for which a better alternative is available [5].

Public lighting is 2% of the overall value [6] of energy consumption in Italy, however, both renewal of technologies and energy rationalization processes could contribute to meeting the three key targets set by EU on climate and energy (i.e., 20% cut in greenhouse gas emissions, 20% of EU from renewables, and 20% improvement in energy efficiency). Among the various and important functions of public lighting is ensuring safety for the movement of traffic and pedestrians. In order to ensure the minimum safety illumination values on roads, specific standards have been set to define minimum luminance and illuminance levels according to the area to be illuminated. In Europe, the updated standard CEN/TR 13201-1:2014 [7] on road lighting provides far greater potential for dynamic control then the previous standard CEN/TR 13201-1:2004 [8], which results in significant energy saving [9,10]. Lighting costs represent up to 25% of the total budget for management of the road network [11], therefore both energy performance indicators and environmental criteria should be adopted when designing smart public lighting systems [12,13]. In particular, safety measures for tunnels and their overall equipment involve a high-energy consumption [14]. The aim of tunnel lighting is to allow traffic to enter, pass through and exit the enclosed section safely. This goal implies that drivers drive into the tunnel without reducing their vehicle speed and are able to see unexpected hazards on the carriageway and stop if necessary [15]. During day time, adequate illumination avoids the "black-hole effect" (i.e., a decrease of the drivers' visual perception) while passing from the outside into the tunnel [16,17]. Therefore, different methods and technologies have been adopted to reduce lighting energy and costs, especially in road tunnels [18–21].

Recently, research has focused on the use of sunlight to reduce energy consumption [22] and related environmental impacts [23]. In some cases, it is possible to use the natural light in an open stretch of the road before the tunnel entrance, that is, a pre-tunnel lighting (PTL) structure is positioned before the access to the "natural" tunnel [24,25]. A PTL is a reticular structure that reduces the luminance in the access zone [26,27]. Tension structures at the tunnel entrance shift the zones with the highest energy consumption; their effectiveness depends on the geometry and orientation, latitude and longitude of the tunnel [28,29]. The construction of these structures implies significant design and construction costs, but the life cycle cost analysis has revealed their economic advantage with respect to the "zero option". Pergolas imply lower energy savings and easier maintenance than tension structures [30]. The introduction of sunlight inside the tunnel with light-pipes [31] or optical fibers [32] is another option for more sustainable tunnels, but this strategy is difficult to use because of the relative position between the sun and light-pipes matrix [33]. When it is not possible to use natural light, the inner surfaces of the tunnel play a crucial role in the tunnel lighting design [34]. For this purpose, the pavement reflection coefficient in the visible spectrum has been recently analyzed as a saving strategy. Salata et al. [16] analyzed four alternative solutions to optimize road tunnel lighting systems with two asphalt pavements with different reflection coefficients and two lighting systems (high-pressure sodium (HPS) luminaries, or HPS and light emitting diode (LED) luminaries). Special asphalts with a high-reflection coefficient reduce the power required, and the energy savings balance their higher installation costs. On the other hand, concrete (light) pavements result in 29% less road tunnel lighting costs compared to traditional asphalt (or black) surfaces; calculations for Italian road tunnel pavements performed by Moretti and Di Mascio [35] have confirmed this. Moreover, the use of concrete instead of bituminous pavements implies a higher level of safety in both ordinary and emergency conditions. Indeed, compared to a flexible pavement, a rigid pavement requires less maintenance activities (which interfere with the traffic flow) [36] and it is not combustible in case of fire [23].

Recently, extensive interest in LED has given rise to new lighting systems in tunnels. LED is the most efficient available technology. Its main characteristics are long life, energy efficiency, environmental friendliness, and zero UV emissions; also, LED illumination produces little infrared light and close to no UV emissions, and excellent color rendering [37]. This technology has been adopted by the Italian government-owned road company ANAS (acronym for Azienda Nazionale Autonoma delle Strade—National Autonomous Roads Corporation, Rome, Italy) to rehabilitate lighting systems in its managed tunnels. In 2018, it launched the Greenlight project, which involves more than 700 tunnel tubes where HPS will be replaced by LED luminaries.

2. The Greenlight Project

The Greenlight project provides for rehabilitation works on road tunnel lighting systems, which consist of replacing outdated high-pressure sodium (HPS) luminaries with state-of-the-art light emitting diode (LED) luminaries. The new devices are equipped in order to wirelessly control the light flow and the energy consumption. The implemented remote control allows adjusting the luminous flux with a point-to-point regulation for each LED luminaire. The wireless management and control system aims to adapt the luminance curve to the different conditions of external brightness, and to diagnose the functional status of the individual projectors. Therefore, the luminous flux can be continuously adjusted according to the external luminance for the reinforcement circuits, and according to the daily time bands for the permanent lighting circuits. LED technology makes it possible to optimize the dimming levels up to 15–20% of their initial flow while maintaining the required perceptive conditions and ensuring a significant reduction in consumption. During the night-time hours, the required visibility conditions inside the tunnel are comparable to those of the open-air sections [16]; only the permanent lighting system is necessary to guarantee the required luminance level. To further reduce consumption, a luminous flux regulation system is also installed to manage permanent lighting according to the reduction in traffic at night.

Compared to SAPs, which only allow a step adjustment for homogeneous groups of fixtures, this technical difference ensures considerable savings for the road manager as it reduces costs and allows for operation flexibility in case of the addition or removal of new elements.

Moreover, the project aims not only to reduce consumption and optimize of tunnel lighting systems, but also to raise safety levels. Indeed, the new luminaries enhance the visibility and quality of the diffusion of artificial lighting inside the tunnel. This is due to the higher color-rendering index (CRI) of LED compared to HPS. CRI is a measure of a light source's ability to show object colors realistically or naturally: the higher the CRI, the better the color perception. Statistically LEDs have CRI values between 70 and 90 or more, while HPS have CRI values not higher than 70 [38]. Road lighting can use lighting systems that have a CRI below 70 because color rendering is not a major issue. However, LEDs offer significant color advantages over HPS, eliminating the monochromatic black appearance of objects illuminated by sodium-bulbs. Therefore, LEDs allow a further reduction in the electricity used for lighting in addition to their longer service life (LED devices have warranty coverage up to 11 years of continuous operation).

Of a total of 1900 tunnels under management, the project involves about 700 tunnel tubes in Italian territory. Greenlight has been divided into eight geographical areas (Figure 1) and two phases with the overall cost estimated as € 155 million (Table 1).

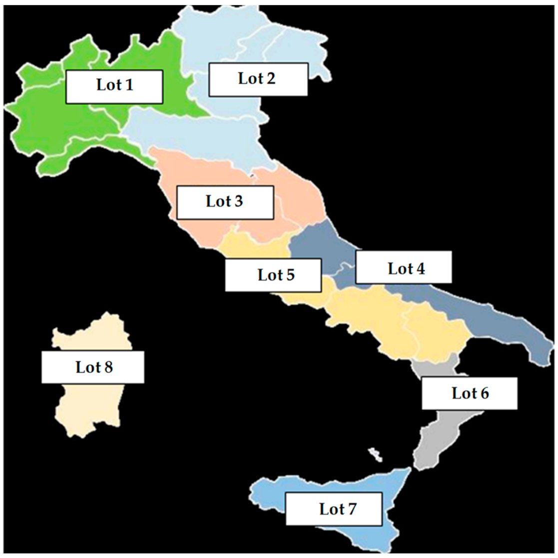

Figure 1. Greenlight project locations.

Table 1. Characteristics of Greenlight.

Lot	Number of Tubes	Overall Length of Tubes (km)	Amount of Estimated Cost (€)
L1	92	70	22,900,000
L2	65	45	13,500,000
L3	145	85	23,800,000
L4	89	75	21,000,000
L5	112	80	23,500,000
L6	117	74	22,300,000
L7	49	58	16,900,000
L8	39	45	11,700,000
Total	708	532	155,000,000

The first phase started in 2018 and is still ongoing: it involves the 147 tubes with the highest energy consumption per unit of length and the overall estimated cost is € 30 million at the end of 2020. Data and the allotted amounts for phase 1 are listed in Table 2.

Table 2. Characteristics of phase 1 Greenlight.

Lot	Number of Tubes	Overall Length of Tubes (km)	Amount Allotted (€)
L1	11	20.37	3,667,000
L2	11	22.22	3,333,000
L3	21	29.41	5,000,000
L4	19	22.22	4,000,000
L5	20	26.67	4,000,000
L6	40	24.07	4,333,000
L7	16	20.00	3,000,000
L8	9	17.78	2,667,000
Total	147	182.74	30,000,000

All works consists of:

- Substitution of old and inefficient lighting HPS systems with more recent and better performing LED ones
- Substitution of the power supply cables
- Substitution of switchboard systems in enclosures
- Installation of control units and brightness probes.

Therefore, there are no modifications, substitutions, or alterations of the existing position and number of luminaries, in both the interior zone and the adaptation zone. Energy-efficient equipment and technologies have been planned in order to monitor the systems and to control the functionality of the equipment during its service life.

3. Methods

The new lighting systems comply with the Italian standard UNI 11095:2011 Lighting of road tunnels [39]. It divides the longitudinal section of a road tunnel into five zones with different levels of required luminance [40,41] as follows:

- Access zone: the stretch of road just before the entrance portal. Its length is equal to the stopping distance at the relevant driving speed. The required luminance value ensures the early and safe detection of an obstacle without reduction in driving speed.
- Threshold zone: the first tunnel section is equal in length to the stopping distance at design speed. The required luminance value is affected by external luminance, which must remain constant and

equal to the outside luminance through half the length of the threshold zone, and it is reduced in a linear manner to 40% at the end of the second part of the section.

- Transition zone: this is the second tunnel section in which luminance values decrease to support the luminance perceived by the driver's eye.
- Interior zone: the internal stretch with a constant luminance value. Its minimum value depends on the design speed and the expected traffic flow. The luminance value of the interior zone is the major difference between European legislated levels of tunnel lighting CIE 88:2004 [42] and the Italian standard UNI 11095 [39]. The former does not set an objective luminance value while the Italian standard establishes a minimum value.
- Exit zone: the final stretch where it is possible to increase the luminance level close to the exit. Such reinforcement/adaptation lighting is not a design constraint for the UNI 11095 standard.

Each zone requires different minimum luminance values as a consequence of the design speed, the meteorological visibility distance, the horizontal lighting in the access zone, the natural luminance, and the optics type, and are calculated using Equations (1)–(3)

$$L_e = c \times L_v = c\,(L_{seq} + L_{atm} + L_{par} + L_{cru}) \tag{1}$$

$$L_t = L_e/(1.9 + t)^{1.4} \tag{2}$$

$$L_t \geq 2 \times L_r \tag{3}$$

where L_e is the maximum luminance value of L_v; c is a coefficient, which depends on the optics; L_v is the veiling luminance; L_{seq} is the equivalent veiling luminance; L_{atm} is the atmospheric luminance; L_{par} is the luminance of the windshield; L_t is the average luminance value in the transition zone; L_{cru} is the luminance of the dashboard; t is the travel time in the transition zone; L_i is the minimum luminance of the permanent lighting circuit; and L_r is the reference luminance value according to [39]. L_{seq} is calculated according to the L20 method, which considers the average value of the luminance in a visual cone of 20°, centred on the line of sight of the driver from the beginning of the access zone.

Since the project involves existing tunnels, no modifications were made to the input data with regard to design speed, meteorological visibility distance, horizontal lighting in the access zone, and natural luminance. Therefore, the stopping distance and the threshold luminance remained the same. The lighting system of each tunnel is composed of one permanent and several reinforcement installations. All devices are arranged in a quincunx geometric pattern in both systems. Counter beam optics create the maximum contrast between existing objects and the road because luminaires are placed above the traffic lanes. The minimum luminous efficacy of each LED luminaire was 105 lm/W and its correlated colour temperature (CCT) was 4000 K; for existing HPS luminaries these average characteristics were 95 lm/W and 2000 K, respectively.

Uniformity performances were settled in agreement with UNI 11095 [39] and UNI EN 13201-2 [43]; these standards require parameters for night-time and daytime, and for each regulation state of the lighting system, which are:

U_0 and $U_t \geq 0.50$ over the carriageway or over one-way lanes;
U_0 and $U_t \geq 0.40$ over all other surfaces and over bi-directional lanes

In areas with constant level of luminance, the standards required are:

$U_l \geq 0.70$ over the carriageway
$U_l \geq 0.60$ over all other surfaces

where:

U_0 is the general luminance uniformity, that is, the ratio between the minimum and the average of luminance values [43].

U_l is the longitudinal luminance uniformity, that is, the ratio between the minimum and the maximum of luminance values [43] determined along the median axle of a lane for the carriageway.
U_t is the transversal luminance uniformity, that is, the ratio between the minimum and the average of luminance values in the same calculus surface section [39].

The software LITESTAR 4D Litecalc [44] was used to design the new lighting systems. It models and verifies the lighting design of road tunnels, and provides numeric and rendered solutions simulating the effects of lighting (shadows, reflections, colour vision and rendering volumes) and obtains a picture of the lighted environment. According to the Italian standard UNI 10439:2001 [45], the assumed maintenance coefficient is equal to 0.8 and the average luminance coefficient is 0.7. These values coincide with those adopted for designing HPS systems.

The adopted software was proven to be suitable for lighting design, since it has an open database where the operator can save product data, do product research, process photometries and spectra or update data automatically; the software was used to realize a real simulation of the results obtained by means of the designed lighting system.

With regard to the lighting design criteria, as previously stated, the luminaires that constitute the permanent lighting system were placed in the same position of the ones previously installed in the tunnel. Each luminaire is equipped with a luminous flux regulation system (transmission module), which communicates with a control unit placed in the cabin. The reinforcement circuits are managed through the veil sensors placed on the external side of the portals, while the permanent lighting circuits are managed through pre-established time cycles. All lighting devices can be modulated to maximize the energy saving performances.

In spite of the design constraints (especially the fixed position of the luminaires), the results of the simulation were satisfying and met all the standard requirements; in particular, with regard to the uniformity, the calculated values generally vary between 0.80 and 0.95 for U_l and between 0.60 and 0.90 for U_0.

Lighting energy and cost calculation take into account the power regulation during the day and the year, for both variations in external luminance and for energy saving.

4. Results

Having referenced the current energy consumption to light the tunnels involved in the first phase of Greenlight, Table 3 summarizes the calculated yearly energy savings for each lot and its overall value. The listed values take into account the switching control and the variable absorbed power during the day (day and night hours) and during the year (sunny, cloudy, or rainy days).

Table 3. Yearly energy savings—first phase.

Lot	Yearly Energy Saving (MWh)
L1	3423
L2	3111
L3	4667
L4	3733
L5	3733
L6	4044
L7	2800
L8	2489
Total	28,000

For each tunnel, the yearly energy saving represents up to 65% of the current yearly energy consumption related to lighting; the value depends on geographical, traffic, and meteorological conditions. At present, the yearly overall consumption for lighting all tunnels managed by ANAS is about 220 GWh, of which 51 GWh is used for the tunnels involved in phase 1 of Greenlight. Therefore, the average energy saving is 55%: this result has both economic and environmental consequences.

Given the average Italian electricity price is 0.16 €/kWh, the economic results and savings obtained in the first phase of Greenlight are listed in Table 4. Moreover, these savings have environmental implications: the saved tons of oil equivalent (TOE) were calculated. According to the Italian Authority for Energy and Gas, the conversion factor of electric energy into primary energy is 0.187 TEP/MWh, and this is the reference value that was adopted to evaluate the effectiveness of the energy efficiency measures.

Table 4. Economic and environmental results—first phase.

Lot	Yearly Saving from Electricity Consumption (€)	Yearly Saved TOE (t of Oil Equivalent)
L1	3,667,000	640.01
L2	3,333,000	781.72
L3	5,000,000	872.67
L4	4,000,000	698.13
L5	4,000,000	698.13
L6	4,333,000	756.25
L7	3,000,000	523.6
L8	2,667,000	465.48
Total	4,480,000	5236.00

Taking into account the expected rebates in the tender phases, ANAS estimated that the actual investment is 30 million euro. Therefore, the economic gains from saving electricity consumption ensure a breakeven point at 7 years after the rehabilitation works, when the project will return its initial investment.

In regard to the environmental issue, the saved impacts from energy non-consumption were calculated using the software package SimaPro 8.0.5.13 [46]. A Life Cycle Impact Assessment was implemented to evaluate the saved environmental impacts in relation to the electricity savings listed in Table 3. The database Ecoinvent 3 was used to assess the parameters describing environmental impacts according to the characterization factors listed in EN 15804:2012+A1:2013 [47]. The examined environmental impact categories (ICs) were: Global Warming Potential (GWP), Ozone layer Depletion Potential (ODP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical oxidation Potential (POCP), Abiotic depletion-elements (ADP-e), and Abiotic depletion-fossil fuels (ADP-f).

The processes included in the environmental analysis of the transmission of high voltage electricity were electricity production in Italy and from imports, the transmission network and the electricity losses. In order to obtain reliable results consistent with the Italian energy market, the production mix was composed of 36.6% of renewable primary energy and 63.4% of non-renewable primary energy (Table 5).

Table 5. Electricity production mix in Italy [48].

Source	Production Share (%)
Coal	13.75
Natural gas	42.34
Oil and other	7.31
Hydro	14.64
Solar	7.68
Wind	5.86
Biomass	6.22
Geothermic	2.20

Table 6 lists the impact categories that were avoided annually due to the total yearly energy saving listed in Table 3.

Table 6. Avoided impact categories—first phase.

IC	Amount	Units
GWP	1.78×10^7	kg CO_2 eq.
ODP	1.35×10^0	kg CFC-11 eq.
AP	6.18×10^4	kg SO_2 eq.
EP	1.51×10^4	Kg $(PO_4)^{3-}$ eq.
POCP	1.84×10^4	kg C_2H_4 eq.
ADP-e	1.93×10^1	kg Sb eq.
ADP-f	2.32×10^8	MJ
GWP	1.78×10^7	kg CO_2 eq.

The Greenlight project represents a big effort on the part of ANAS, the Italian government-owned road company to rehabilitate and improve the lighting systems in its tunnels. The investments are significant, for example, for the rehabilitation works completed in 2018, the total cost was 6 million euros (Figure 2), and in 2019, works worth 13.5 million euros are in progress or planned (Table 7).

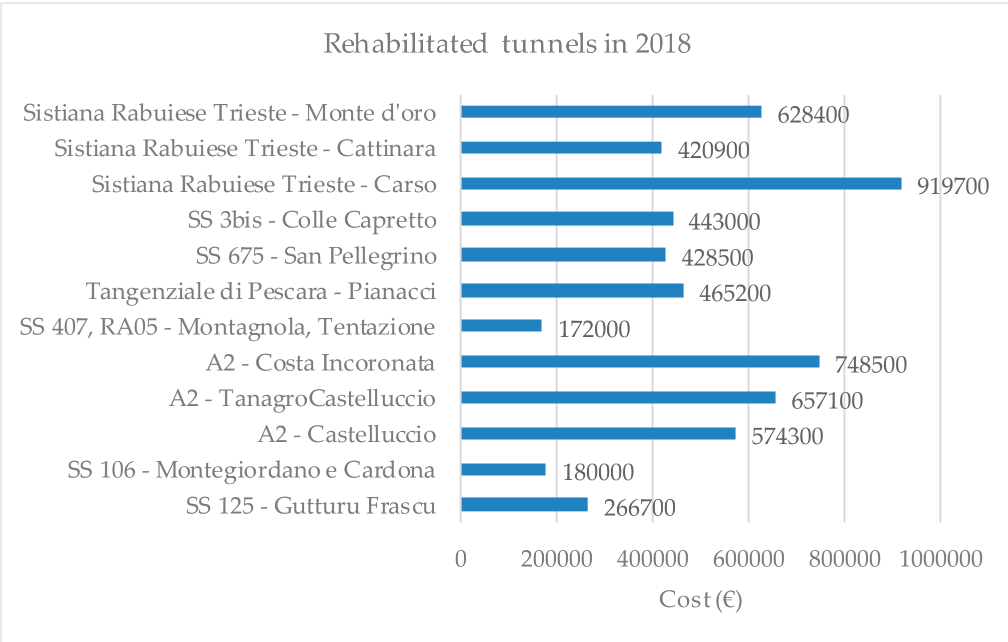

Figure 2. Completed works in 2018.

Table 7. Planned and on-going works in 2019.

Lot	Planned and On-Going Works (€)
L1	1,177,750
L2	1,869,690
L3	3,059,210
L4	2,573,350
L5	1,330,420
L6	2,857,680
L7	0
L8	687,270
Total	13,555,370

Data in Table 7 were also analyzed in order to correlate the required investment to the tunnel length (L): Figure 3 shows the results obtained for 32 tunnels (their overall length is 39,663 m) of phase 1.

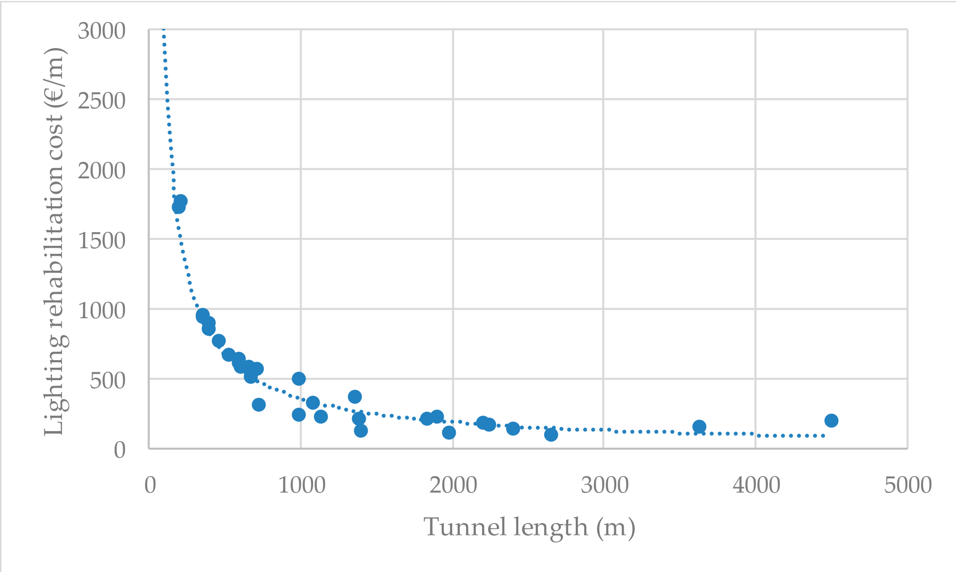

Figure 3. Tunnel length vs. rehabilitation lighting costs per unit length.

As shown in Figure 3, a correlation curve between *L* and the lighting rehabilitation cost per unit length (c_l) was identified (Equation (4)):

$$c_l = 182339\ \mathrm{L}^{-0.901} \tag{4}$$

where *L* is expressed in m and c_l is in €/m.

The coefficient of determination R^2 of the dashed trend line is 0.87. The obtained curve is valid under two important hypotheses about the cost of luminaries and the layout of the lighting systems.

With regard to the cost, the unit prices comply with those currently valid in Italy [49]; the price of each luminaire ranges between € 395 for elements with less than 3000 lm luminous flux and € 1798 for elements with more than 41,500 lm luminous flux. Regarding the layout of the lighting systems, the number and the position of LED luminaries coincide with those of existing HPS luminaries. Thus, the distance between LEDs could be less without the restriction of having to replace the HPS at the same distance, and the total initial cost of the luminaires in the interior zones could be higher.

5. Discussion

For ANAS, tunnel lighting is the principal cost item in the energy budget expenditure: at present, the yearly consumption for tunnel lighting is about 230 GWh. Therefore, the Greenlight multi-year project aims to reduce energy consumption for lighting in its road tunnels. It consists of using equipment and technologies characterized by high energy efficiency (i.e., LED luminaries) and balancing environmental-economic needs and the operational limits due to pre-existing structures.

Greenlight aims to improve and standardize safety standards and service to road customers, as well as to optimize energy consumption, especially in more energy-intensive lighting systems. The high CRI, the luminous efficiency and the high visual comfort of LED luminaries allow for significant reductions in the energy consumption with the same luminance on the road surface. For each luminaire considered in the project, the minimum CRI is 80, the minimum luminous efficacy is 105 lm/W, and its CCT is 4000 K. Furthermore, the installation of luminance sensors at tunnel entrances permits the internal luminance to be monitored continuously and verifies the state of efficiency and reliability of the system. Lighting monitoring is ensured by specific latest-generation software and its results are dealt with in real time. Moreover, in contrast to the HPS luminaries, during day hours this type of luminaire permits point-by-point adjustment of the internal illumination in accordance to the external luminance, in order to optimize the luminous flux. Therefore, the wireless management and control system diagnoses the functional status of the individual projectors, and also adapts the brightness of each luminaire to different conditions. During night hours, only permanent lighting remains in operation to guarantee the required luminance level. In order to further reduce consumption, a luminous flux adjustment system is also installed for permanent lighting, which takes into account the reduction of vehicular traffic at night.

The benefits arising from Greenlight are related to users' safety, road management savings, and environmental protection. ANAS estimates that the return on investment is 7 years, this has been calculated considering only energy savings, without the cost of maintenance. Therefore, the return on investment could be a shorter time because of the durability of LED which is greater than HPS. Considering the costs and the effectiveness of the investment, it should also be noted that the knowledge gained to date suggests there is a correlation between the lighting rehabilitation cost and the length of the tunnel. This analysis was presented above (see Figure 3) and this finding might help to expedite the assessment of the cost of road tunnel LED lighting systems: it fits with the variability in lighting rehabilitation costs per unit length that is caused by the luminance requirements laid down by the reference standard UNI 11095.

6. Conclusions

Renewal of technologies and energy rationalization processes could contribute to meeting the sustainability targets set by the European Union on climate and energy. Within this framework, ANAS, the Italian government-owned road company launched the Greenlight project to replace HPS tunnel lighting systems with state-of-the-art LED luminaries. The new systems will reduce electricity consumption by up to 50% of the current values; additionally, the lighting quality inside the tunnel will be enhanced thanks to better uniformity and color temperature of the new luminaries.

The initiative is composed of two phases: the first one will account for 45 million euros and the second one for about 110 million euros. Until now, the on-going first phase involves 147 tubes: their new lighting systems cost 30 million euros (allotment volume) and ensure 28 GWh saved energy every year (on average 55% of the current consumption). The economic saving provides a total return over less than seven years and has direct environmental effects. According to the European standard EN 15804, the avoided yearly emissions of greenhouse gases are 17,000 t of CO_2 eq., while saved abiotic and fossil resources are 19.3 kg of Sb and 230 TJ, respectively.

The presented on-the-field experience permitted us to correlate the tunnel length to the rehabilitation cost per unit length; the high value of the coefficient of determination corroborated the result, which could be useful to road managers pursuing environmental, economic and safety goals with tunnel LED lighting.

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