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Comparative Study of Energy Savings for Various Control Strategies in the Tunnel Lighting System

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Abstract: Tunnel lighting is the most significant component in total energy consumption in the whole infrastructure. Hence, various lighting control strategies based on light-emitting diode (LED) technology have been investigated to conserve energy by decreasing luminaires' operating time. In this study, four kinds of tunnel lighting control strategies and the development of their associated technologies are evaluated: no-control low-consumption lamps (LCL), time-scheduling control strategy (TSCS), daylight adaptation control strategy (DACS), and intelligent control strategy (ICS). This work investigates the relationship between initial investment and electrical costs as a function of tunnel length (*L*) and daily traffic volume (*N*) for the four control strategies. The analysis was performed using 100-day data collected in eleven Chinese tunnels. The tunnel length (*L*) ranged from 600 m to 3300 m and the daily traffic volume (*N*) ranged from 700 to 2500. The results showed that initial investment costs increase with L for all control strategies. Also, the electricity costs for the LCL, TSCS, and DACS strategies increased linearly with *L*, whereas the electricity cost for the ICS strategy has an exponential growth with *L* and *N*. The results showed that for a lifetime equal to or shorter than 218 days, the LCL strategy offered the best economical solution; whereas for a lifetime longer than 955 days, the ICS strategy offered the best economical solution. For a lifetime between 218 and 955 days, the most suitable strategy varies with tunnel length and traffic volume. This study's results can guide the decision-making process during the tunnel lighting system's design stage.

Keywords: lighting control system; energy savings; control strategy; LED lighting

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1. Introduction

Urban sustainability is one of the many challenges the world faces today, with development constrained by limited land space. Thus, road tunnels and underground passes are becoming popular for overcoming land limitations. Their implementation offers various other benefits such as minimizing the damage to the environment, reducing traffic congestion and vehicle mileage, and protecting land resources [1–3]. Statistical data in ref. [4] showed that at the end of 2020, there were 21,316 road tunnels in China with a total length of over 21,999 km. From these tunnels, there were 1394 extra-long (length > 3000 m) tunnels and 5541 long (1000 < length < 3000 m) tunnels. The report also showed that China has the largest number of tunnels and has the greatest potential for further development in the future. Although this research applies to both road tunnels and urban underground passes, for the sake of simplicity, we will talk only about "road tunnels" in the rest of the article.

Road tunnels are tubular structures, enclosed except for their entrance and exit. The lack of adequate lighting at the entrance of tunnels can be perceived as a "black hole" by drivers [5] and can increase the risk and severity of traffic accidents [6]. The aim is to decrease the consumption of the lighting installation and environmental impact whilst improving drivers' visual adaptation, thus ensuring traffic safety. All strategies used require the use of green energy for the tunnel lighting. Green energy comes from natural sources such as sunlight, wind, tides, and geothermal heat. The solutions used up to date can be grouped into three:

1. Shifting the threshold zone (most consuming area) out of the tunnel by utilizing structures allowing certain solar flux to pass. These structures are placed right before the portal gate of road tunnels and their effect is to reduce the amount of electrical luminous flux requirement, that is, complementing it with natural light. Gil-Martín and Peña-García [7,8] applied this strategy with concrete pergolas and without diffusers to optimize the uniformity. Drakou et al. [9] used a punctured structure (filter) before the tunnel entrance to mitigate the elevated difference of luminance in the threshold zone, enhancing the incoming drivers' visual adaptation. Cantisani et al. [10,11] proposed new alternative ways to use these shifting pre-tunnel structures. Wang et al. [12] proposed setting the dark shading sheds near the entrance and the light color shading sheds at the other end far away from the tunnel entrance to achieve a smooth luminance transition. Zhao et al. [13] proposed that a tunnel entrance sunshade should be set up to mitigate the sudden change of the luminance intensity at the tunnel entrance and proposed that the sunshade's length should be less than the SSD (safe stopping distance). However, utilizing the shading structures could result in increased maintenance workload and poor pavement illuminance uniformity.
2. The second option is using the light of the sun to power lighting devices or simulate projectors themselves. Lu et al. [14] used a solar LED (light-emitting diode) tunnel lighting system to reduce the high operating cost and high energy consumption. Peña-García and Gómez-Lorente [15] showed that installing black solar panels around the tunnel portals decreases the energy requirement in the entire tunnel, which leads to significant savings due to the darkening in the tunnel surroundings with lower lighting requirements and also the energy produced by the panels. Qin et al. [16] used solar optical fiber lighting to enhance tunnel lighting, reduce energy consumption, and improve lighting quality and environmental protection, whereas Gil-Martín et al. [17] and Peña-García et al. [18] used light pipes for this same purpose. Yao and Ning [19] developed a new system for improved illumination by using enhanced parallel sunlight on the tunnel entrance. This system achieved highly efficient and long-distance sunlight transportation through optical path transformation and reflection. Zhao et al. [20] proposed a solar power supply system that used solar photovoltaic power generation based on hybrid wind-solar power generation. Zuo [21] proposed an energy-saving power supply system based on wind-light complementary and hybrid energy storage. These authors used solar energy to provide lighting at the tunnel entrance and wind turbines at the top of the tunnel to complement the tunnel's power supply system. Peña-García [22] proposed the SLT equation, which established the theoretical basis to foresee energy savings and calculate the necessary parameters with any strategy using sunlight in road tunnels from either perspective, i.e., shifting of the threshold zone and/or direct injection of light inside the tunnel.
3. Then, there is the option to install or retrofit the lighting system with cost-effective luminaires to balance the energy consumption and provide adequate luminance. LED luminaires provide notable benefits of long life, high luminous efficiency, short start-up time, low power consumption, and high color temperature. These luminaires are already being applied to replace conventional light sources for tunnel lighting [23–25]. Salata et al. [26] used a mixture of high-pressure sodium (HPS) lamps and LEDs in the tunnel threshold zone to reduce the high costs. Shailesh et al. [27] compared the economic performance of LED and HPS lamps for road lighting. The results showed that LED lighting has a better performance than HPS luminaires due to decreased operating costs and increased savings; thus, there is a larger potential for improving road safety using cost-effective LED lighting. Kimura et al. [28] presented findings that

better visibility in the tunnel can be achieved by increasing the luminance uniformity of LED under the equivalent luminance, saving up to 20% electric energy. Ye [29] studied the differences in luminance and energy costs of the Huayingshan tunnel when replacing HPS with LED luminaires. The results showed that the LED lighting system could save as much as 63.6% in energy costs.

In parallel with the abovementioned three main strategies, which are compatible among themselves, it is also effective to provide devices to guide drivers' sight in tunnels and improve drivers' visual adaptability. Han et al. [30,31] proposed that setting delineators in tunnels could change the monotonous environment and increase drivers' attention, decreasing drivers' anxiety and mental workload and ensuring their driving safety. Du et al. [32] investigated the effect of reflective ring numbers on drivers' curvature perception at different radii tunnels using a driving simulator. The experimental results showed that drivers' reaction times slightly decrease when using reflective rings. In particular, three reflective rings are recommended because they can effectively improve drivers' curvature perception and control the reaction time within a reasonable range. Song et al. [33] designed three groups of comparative experiments using a driving simulator to investigate the influence of signs and markings on drivers' movement. The experimental results showed that a thin red pavement and speed limit sign before the tunnel entrance significantly affected the speed standard deviation's control. However, the sightline guidance system's setting lacks a basis; it is difficult to unify the size, installation distance, and sightline guidance facilities' combination due to a lack of reference standards [34].

The solutions adopting LEDs and integrating sensors and communication technologies enable lighting control systems to become smarter with greater sensing, data processing, and connectivity. Qin et al. [35] proposed an energy-saving tunnel lighting control system where the LEDs operate in continuous low-power mode when there are no vehicles in the tunnel. In this condition, the energy consumption can be as low as 10% of the maximum power. When a vehicle's approach is detected, the inside tunnel luminance is determined by vehicle speed, traffic level, and ambient luminance. Aksoy [36] proposed an intelligent tunnel lighting control system that sets the LEDs' luminance to the lowest level of CIE-88 standard when the vehicles are not inside the tunnel at night. Otherwise, the tunnel is divided into 10 lighting groups. The luminance of the two groups' LEDs in front of the car is increased when the vehicle enters the next group, with the other groups maintained in tunnel-saving mode. Zhao et al. [37] constructed an energy-saving fuzzy tunnel lighting control system based on IoT (Internet of Things) technology. There are three input variables (L: real-time exterior environmental luminance, V: vehicle speed, and N: traffic volume) and one output variable (the real-time luminance of sodium lamps) in this fuzzy system, which have five, five, three, and 75 linguistic levels, respectively. Spor et al. [38] implemented the fuzzy logic control system used an FIS (fuzzy interface system) in MATLAB software. In this system, the inputs are the sun location, weather conditions, and the year's season, while the outputs are luminous intensity and color temperature. Moreover, the sun position has nine different cases (night, early morning, sunrise, morning, noon, afternoon, sunset, evening, and again, night), the year's season has two cases (summer, winter), the luminous intensity has 11 cases (0, 10, 20, . . . 90, 100), and the color temperature has five cases (candle, warm white, daylight, cool light, and blue sky). Doulos et al. [39] proposed a no-cost finetuning method for switching lighting stages based on the traffic weighted L_{20} luminance to minimize lighting consumption in existing tunnels. Total energy consumption and the corresponding energy savings for four scenarios were examined. The results showed that the energy saving could reach 54% when replacing existing lamps with LEDs.

Most current tunnel lighting systems changed from outdated conventional lamps to state-of-the-art LED lamps without modifying the position and quantity of the existing lamps. This change resulted in significant energy savings and provided opportunities to further increase savings by automatically regulating the luminous flux according to different circumstances [40]. Moreover, as mentioned above, various luminance control strategies have been explored for LED technology. However, few studies guide the reader on selecting the right lighting control strategy based on tunnel length and traffic volume. This paper compares the performance and energy-saving potential of various lighting control strategies based on the SCADA (Supervisory Control and Data Acquisition) tunnel lighting system. Eleven tunnels in China with different tunnel lengths and traffic volumes were examined. Then, we provide suggestions on how to select a lighting control strategy for various scenarios.

2. Tunnel Lighting Controls: Strategies and Technologies

The tunnel lighting control strategy is a conceptual description of how to modify the amount and quality of illumination provided by a lighting system to suit the luminance and human vision comfort requirements. The strategy provides specific technology methods to control the lighting system while representing a significant contribution to tunnel energy consumption.

Tunnel lighting control strategies have gone through two successive stages: manual control and automatic control strategies [41]. The automatic control strategy implements energy-saving by decreasing lamps' operating time based on various factors such as time of day, ambient luminance, and the presence or absence of vehicles. Thus, this strategy consists of time-scheduling control, daylight-adaptation control, and intelligent control. In this section, the performance, hardware devices, and energy consumption of several control strategies are investigated.

2.1. Manual Control Strategy

Manual control is the earliest and most straightforward method employed in tunnel lighting. This simple strategy allows users to turn an individual lamp or a group of lamps on or off using a manual switch or dim the intensity to intermediate light levels with dimming regulators inside the tunnel. Nowadays, advanced tunnel lighting systems provide new flexible ways for users to control the lighting level right from their computer screens and smartphone applications. The manual control strategy scheme is shown in Figure 1.

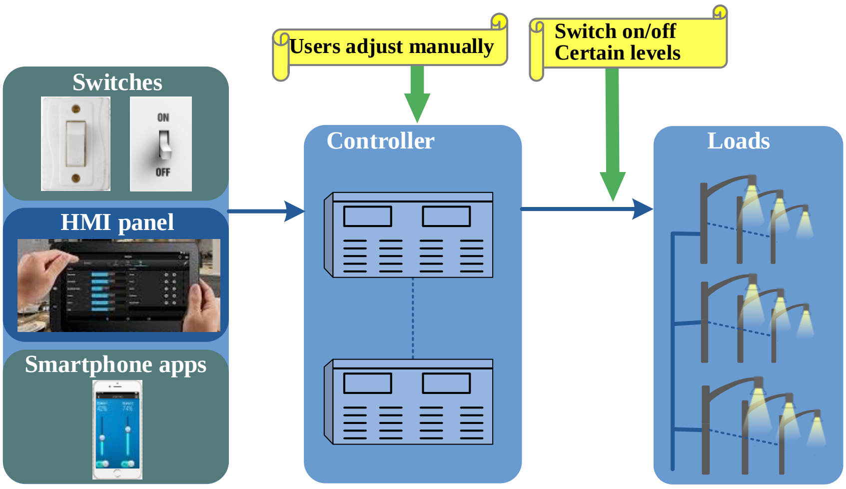


Figure 1. Manual control scheme.

2.2. Time-Scheduling Control Strategy

Figure 2 presents the time-scheduling control scheme for tunnel lighting. The time-scheduling control strategy enables the controlled lights to turn on, off, or dim to different lighting levels automatically based on specific time-slots of the day or based on the sunset and sunrise.

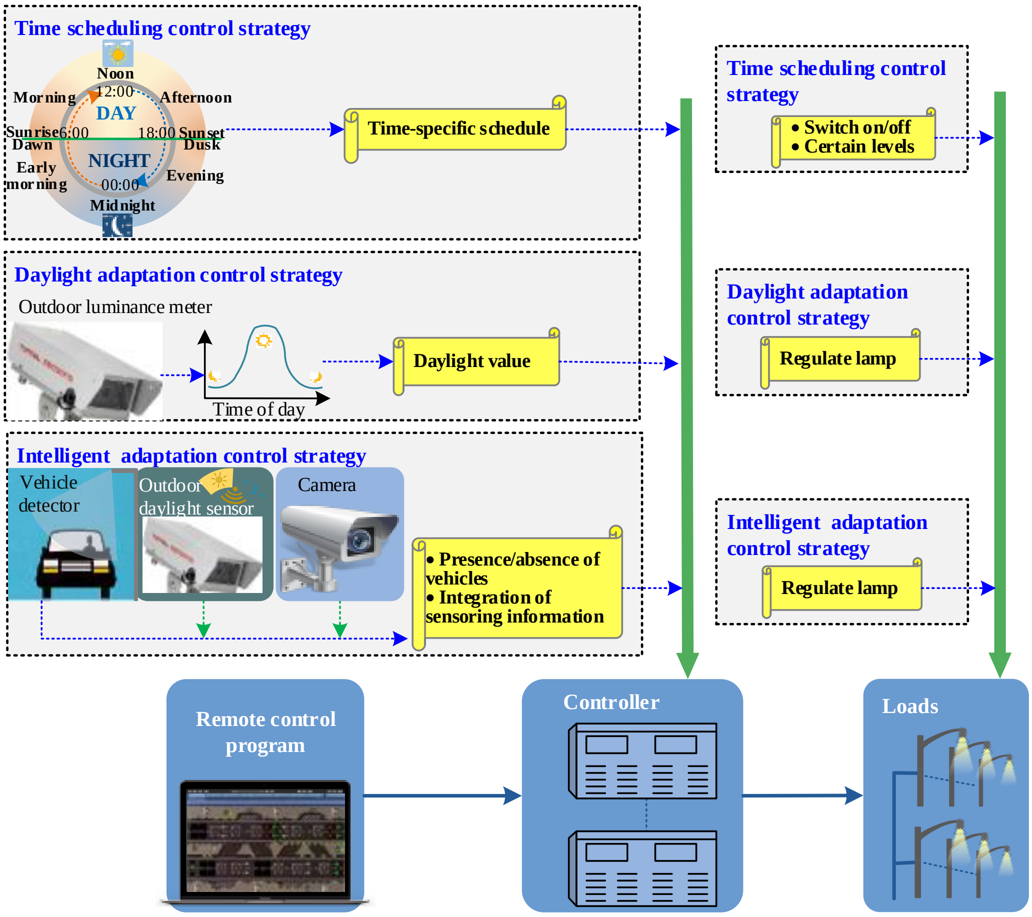


Figure 2. Time scheduling, daylight adaptation, and intelligent control schemes.

2.3. Daylight-Adaptation Control Strategy

For the daylight-adaptation control strategy, lamps' outputs in the tunnel interior are dimmed following the ambient luminance to meet the luminance requirements for drivers' eye adaptation. A luminance meter deployed outside the tunnel entrance is used to monitor the ambient illuminance level, which varies with the tunnel orientations, climatic conditions, and geographical locations. The strategy enables the controller to use a simple control algorithm, such as producing luminous levels in a fixed proportion to the estimated daylight level, to dim lamps. This control scheme is illustrated in Figure 2.

2.4. Intelligent Control Strategy

The intelligent control strategy uses artificial intelligence algorithms (e.g., fuzzy control algorithm, neural network) to match luminance to drivers' needs under different environment stages and traffic levels while minimizing energy consumption. The lamps' lighting intensity in this control strategy is dimmed taken into account actual current demand, such as weather conditions, traffic volume, vehicle speed, and vehicle presence/absence. This control scheme is shown in Figure 2.

Vehicle detectors employ motion-sensing technology to identify the presence of a vehicle and vehicle speed in a given range of space. The technology of sensors can be of different types and costs. Infrared, microwave, ultrasonic, and other types are currently in use and each has its pros and cons. Despite the difference in the technology used to detect the vehicles, the tunnel lighting system's operation's underlying algorithm is very similar.

The above brief discussions indicate that all control strategies require several sensors except for the manual control strategy. Savings and consumption reports can vary based on which type of control strategy has been implemented. In the next section, data of tunnel lighting for eleven tunnels in China are used to compare the hardware cost and energy savings produced by four common control strategies. The tunnel lighting for all 11 tunnels is based on a SCADA system.

2.5. Comparison of Hardware Cost and Energy-Saving for Four Control Strategies

In this section, Madang tunnel is used as the case study to evaluate four tunnel lighting control strategies in terms of hardware cost and energy savings. The evaluated control strategies are no-control low-consumption lamps (LCL), time-scheduling control strategy (TSCS), daylight-adaptation control strategy (DACS), and intelligent control strategy (ICS).

The LCL control strategy maintains a maximum 24-h luminance level, regardless of the weather and vehicle conditions. This method leads to large energy consumption; however, it does not require any equipment for its operation.

A programmable scheduling routine regulates the LED light fixtures for the TSCS. The scheduling is based on the time of day. For tunnel lighting, as shown in Table 1, the 24-h period is often divided into six sub-periods, each with a luminance level. Figure 3a presents the hourly lighting for the LCL and TSCS strategies.

Table 1. Scheduling routine of TSCS.

Sun Location	Time of Day	Luminance Level
Early morning	02:00~06:00	60%
Morning	06:00~10:00	80%
Noon	10:00~14:00	100%
Afternoon	14:00~18:00	80%
Evening	18:00~22:00	60%
Midnight	22:00~02:00	40%

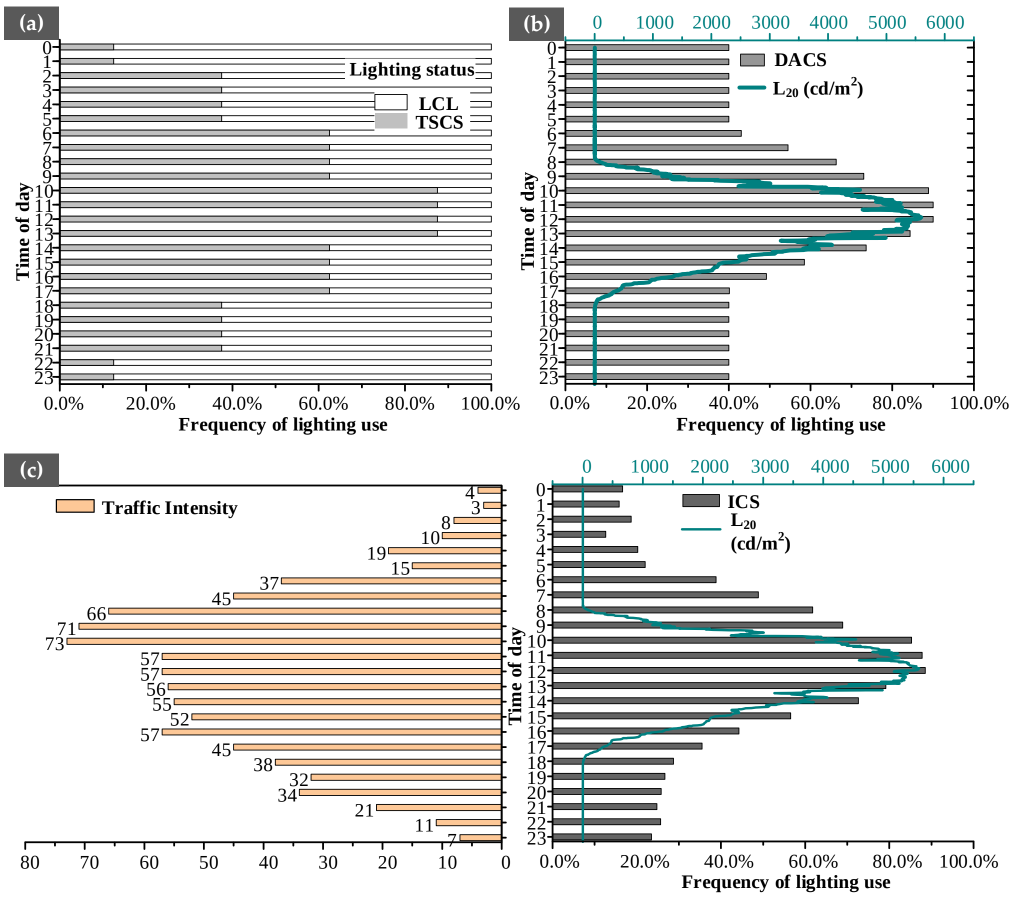


Figure 3. Hourly lighting luminance level for various control strategies.

For DACS, the light levels of light fixtures are controlled in response to varying ambient luminance, regardless of vehicle presence and vehicle speed. Ambient luminance is read from the luminance meter placed 1.5 m above ground at the SSD from the tunnel entrance port. The data collection interval is 10 s. Figure 3b shows the hourly lighting for the DACS strategy.

For the ICS, this study considers the "vehicle in, light on; vehicle out, light off" approach [23]. The light levels of light fixtures depend on vehicles' presence, vehicle speeds, and ambient luminance. LEDs are dimmed to their minimum luminance level when there are no vehicles in the tunnel; otherwise, the luminance is varied with the ambient luminance and vehicle speed. Vehicle detectors, luminance meters, and surveillance cameras are required in the system. The hourly lighting for this strategy for one day is shown in Figure 3c.

Table 2 presents the itemized initial installation costs of various control strategies in the Madang tunnel in China. The total cost in Table 2 does not include maintenance and operation costs. According to Table 2, the initial installation cost for the LCL, TSCS, DACS, and ICS strategies are $38,432, $51,756, $53,613, and $60,795, respectively. This shows that the LCL strategy has a lower initial installation cost compared to the TSCS, DACS, and ICS strategies.

Table 2. Comparison of initial installation costs for various control strategies in Madang tunnel.

	Category				**Item**		**Qty.**	**Cost Per Unit/$**
	ICS	**DACS**	**TSCS**	**LCL**	LED lamps	30 W	391	41.78
						50 W	59	47.97
						80 W	16	69.64
						140 W	62	95.95
						240 W	21	123.8
					Local optical transceiver		1	1121.87
					Remote optical transceiver		8	1060.08
					Server		1	3961.74
					Local dimming controller		1	1315.42
					Remote dimming controller		8	1005.91
					Luminance meter		1	1857.07
					Infrared sensor		2	79.7
					Microwave detector		2	162.03
					Surveillance camera		12	558.2
Total	$60,795	$53,613	$51,756	$38,432				

The data in Figure 3 and Table 2 are combined in Figure 4. As can be observed from Figure 4, the ICS strategy could consume about 10 percent less electricity than the DACS strategy, 27 percent less than the TSCS strategy, and 57 percent less than the LCL strategy. Likewise, the system cost for the ICS strategy is 19 percent higher than the DACS strategy, 24 percent higher than the TSCS strategy, and 58 percent higher than the LCL strategy.

Because traffic volume and tunnel length could impact the energy saving of the ICS strategy, data collected in eleven tunnels with different lengths and traffic conditions were used to determine a relationship between these variables. Table 3 presents the advantages and disadvantages of several control strategies.

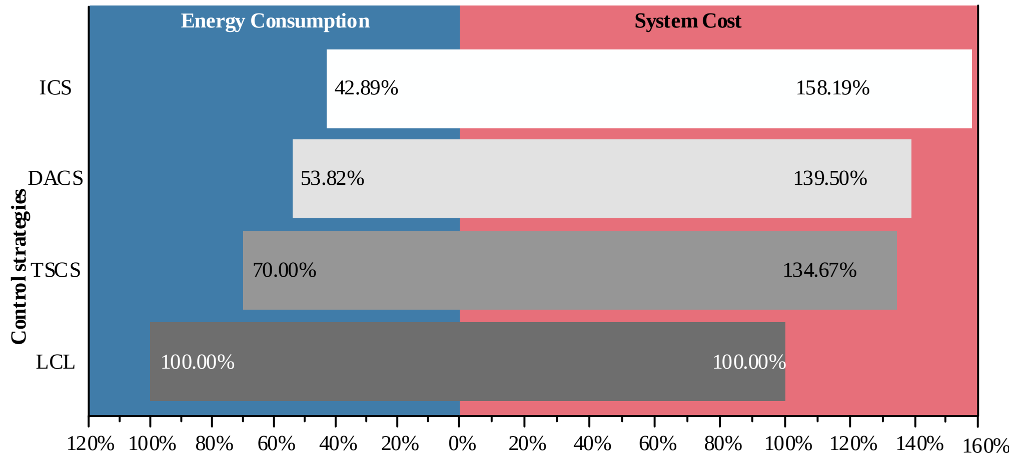


Figure 4. Relationship between control strategy and energy consumption/system cost.

Table 3. Lighting control strategies' analysis.

Strategy	Main Advantage	Main Disadvantage
Manual	- Easy to implement and more stable - Flexible lamp selection - Low system cost	- Considerable energy consumption - Poor luminance continuity and uniformity
Time scheduling	- Simple programming and circuit design - Intermediate potential of energy saving	- Poor luminance continuity - Relatively high system cost - Hardly have any energy-saving effect
Daylight adaptation	- Intermediate complex of control algorithm - Achieved continuous tuning of lighting level - Intermediate potential of energy saving	- Relatively high system cost - Consumes more energy at low traffic volume condition
Intelligent	- Achieved continuous tuning of lighting level - High potential of energy saving	- Highly complex control algorithm - High system cost

3. Materials and Methods

3.1. Tunnel Information

The study presented in this article is carried out by analyzing eleven representative tunnels in the Jilin Province, China. The tunnels include short tunnels ($L \leq 500$ m), medium-long tunnels ($500 < L \leq 1000$ m), long tunnels ($1000 < L \leq 3000$ m), and extra-long tunnels ($L > 3000$ m). The basic characteristics of the eleven tunnels are presented in Table 4. All tunnels are double-arched, have two lanes, and the designed speed is 80 km/h. The overall road width is 10.5 m, the lane width is 3.75 m, the left shoulder width is 1.5 m, and the right shoulder width is 1.5 m.

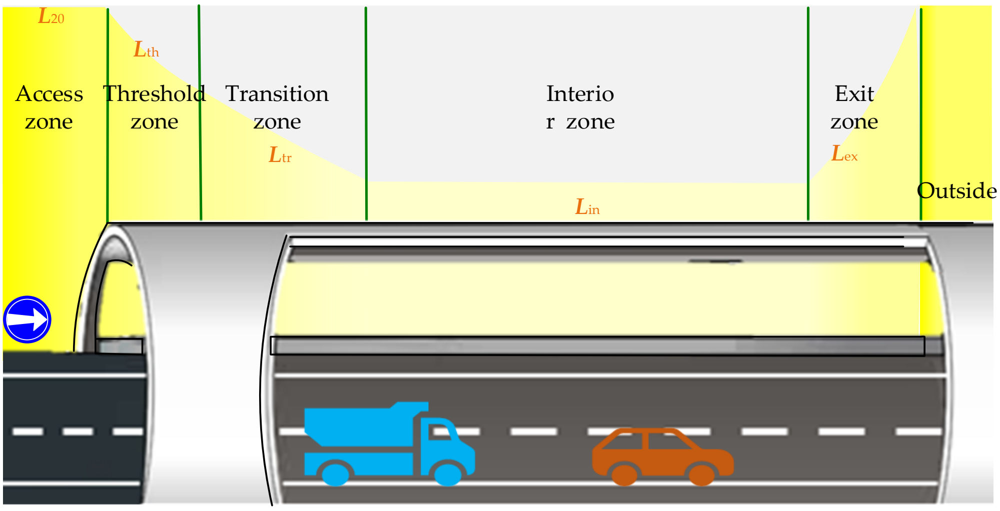
3.2. Luminance Demand in Tunnel Lighting System

Road tunnels require safe and reliable lighting, maximizing drivers' visibility, which helps drivers identify the obstacles and other vehicles in the tunnel and plays an essential role in accident prevention. Tunnel lighting must provide very high amounts of luminance intensity during the daytime (when drivers are going from very bright to darker environments), especially during the first part of the tunnel, to eliminate "black hole" phenomena and ensure correct visual adaptation. There is no tunnel luminance change during the nighttime, and the average road surface luminance inside the tunnel must not be less than 1 cd/m^2 based on the CIE Publ. 88 [42] and China-JTG-201 [43] standards.

Table 4. Basic characteristics of the eleven examined tunnels.

Tunnel	Length (m)	Tunnel Type
1	720	Medium-long
2	660	Medium-long
3	1018	Long
4	1270	Long
5	1557	Long
6	1770	Long
7	2024	Long
8	2250	Long
9	2520	Long
10	2910	Long
11	3215	Extra-long

To allow the driver's eyes to adapt safely to the changing lighting levels during the daytime, the CIE Publ. 88 and China-JTG-2014 standards divide the tunnel's longitudinal section into five reference zones, as shown in Figure 5. These reference zones are defined based on the daylight lighting requirements: access zone, threshold zone, transition zone, interior zone, and exit zone. The luminance of the threshold zone is directly related to the luminance level of the exterior environment. The interior zone is used to provide basic lighting. JTG-2014 is slightly different from CIE Publ. 88, but many provisions in JTG-2014 referenced CIE Publ. 88. As defined in ref. [43], threshold zone 1 is divided into two subzones, and transition zone 2 into three subzones, while the exit zone is divided into two subzones. In each zone, the luminance value decreases progressively, and the luminance of each subzone can be calculated based on Table 5.



Note: L_{20} is the average luminance value measured in a 20°conical field of view define at the SSD from tunnel entrance. L_{th}, L_{tr}, L_{in}, L_{ex} are luminance of threshold zone, transition zone, interior zone and exit zone, respectively.

Figure 5. Lighting zones of a road tunnel.

3.3. Hardware Structure of Tunnel Lighting Control System

The tunnel facilities were installed with fully automated and centralized electromechanical services using SCADA (Supervisor Control and Data Acquisition) technology to implement intelligent control and monitor the tunnel lighting system.

The advantages of the SCADA tunnel lighting system are briefly described below:

Control and operate lighting system remotely: Connect to the remote SCADA monitoring system to provide even greater control and visibility.

Optimize lighting throughout your tunnel: Decrease the black hole effect to maximize safety with L20 tunnel controls explicitly built for LED lighting technology.

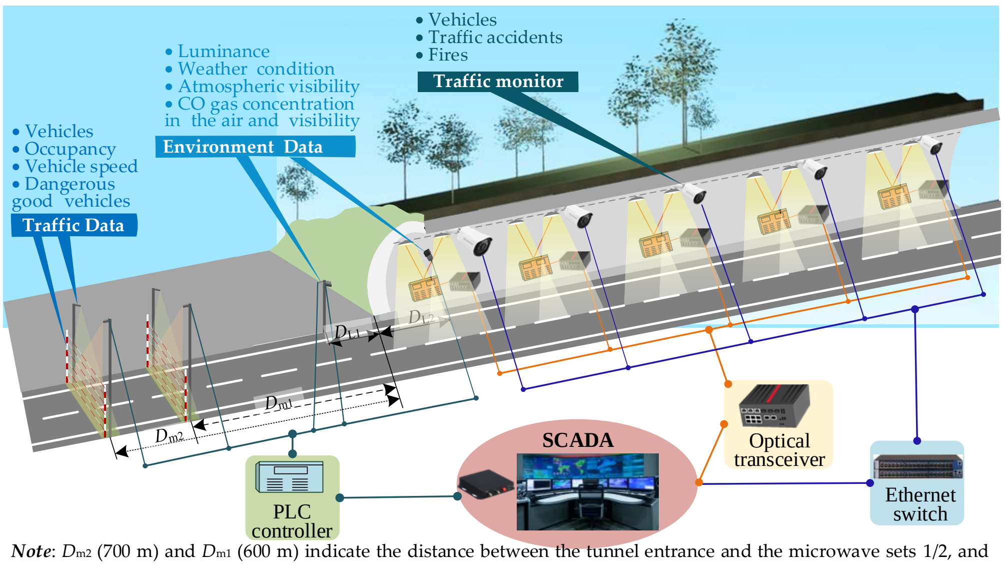
Reduce operational cost: Energy-efficient LED lighting delivers an excellent driver experience at a lower cost.

Table 5. Luminance and length of tunnel zones shown in Figure 5.

Tunnel Section		Luminance (cd/m^2)		Distance (m)
Threshold zone 1	$L_{\text{th1}} =$	$0.0005v - 0.013) \times L_{20}$ $(0.355v + 0.0002N\ (v - 29) - 9.03) \times L_{20}/850$ $(0.0007v - 0.0188) \times L_{20}$	$N \leq 350$ $350 < N < 1200$ $N \geq 1200$	$D_{\text{th1}} = 0.5(1.154D_{\text{s}} - (h - 1.5)/\tan 10°)$
Threshold zone 2		$L_{\text{th2}} = 0.5 \times L_{\text{th1}}$		$D_{\text{th2}} = D_{\text{th1}}$
Transition zone 1		$L_{\text{tr1}} = 0.15 \times L_{\text{th1}}$		$D_{\text{tr1}} = (D_{\text{th1}} + D_{\text{th2}})/3 + v_{\text{t}}/1.8$
Transition zone 2		$L_{\text{tr2}} = 0.05 \times L_{\text{th1}}$		$D_{\text{tr2}} = 2v_{\text{t}}/1.8$
Transition zone 3		$L_{\text{tr3}} = 0.02 \times L_{\text{th1}}$		$D_{\text{tr3}} = 3v_{\text{t}}/1.8$
Interior zone	$L_{\text{in}} =$	$0.0007v^2 - 0.0693v + 2.6$ $0.0005v^2 - 0.0207v + 0.9$ $0.0012v^2 - 0.0732v + 2.1$	$N \leq 350$ $350 < N < 1200$ $N \geq 1200$	$D_{\text{in}} = L - D_{\text{th1}} - D_{\text{th2}} - D_{\text{tr1}} - D_{\text{tr2}} - D_{\text{tr3}} - D_{\text{ex1}} - D_{\text{ex2}}$
Exit zone 1		$L_{\text{ex1}} = 3 \times L_{\text{in}}$		$D_{\text{ex1}} = 30$
Exit zone 2		$L_{\text{ex2}} = 5 \times L_{\text{in}}$		$D_{\text{ex2}} = 30$

Note: (v) is vehicle speed (km/h); (N) is traffic volume (veh/(h·ln)); (D_s)is the stopping sign distance (SSD, m); h is the tunnel clearance height (m); (v_t) is the design speed (km/h). In this study, v_t = 80 km/h, D_s = 100 m, h = 6.0 m.

Figure 6 depicts the hardware schematic of the SCADA tunnel lighting system. As shown in this figure, a SCADA tunnel lighting system involves LED luminaires, LED dimming controllers, communication infrastructure, remote terminal units, servers, surveillance of roadways, real-time collection of outside luminance data, and monitoring of air quality and visibility levels inside and outside the tunnel.



Note: D_{m2} (700 m) and D_{m1} (600 m) indicate the distance between the tunnel entrance and the microwave sets 1/2, and the microwave sets 3/4. D_{L1}: Distance between luminance meter and tunnel entrance port (100 m). D_{L2}: Distance between CO/VI detector detector and tunnel entrance port (200 m).

Figure 6. Schematic of the hardware of the SCADA tunnel lighting system.

Traffic management equipment consists of microwave detectors, infrared detectors, and surveillance cameras. Microwave and infrared detectors are used to monitor the tunnel's traffic flow, which helps regulate lighting. Surveillance cameras are used to maintain a continuous flow of traffic information, which helps in decision-making during emergencies, such as accidents or car stopping. The surveillance cameras are installed every 150 m in the tunnel. Environmental monitoring equipment includes a luminance meter and visibility and CO/VI detectors. The daylight sensor is used to measure the ambient luminance to determine the luminance level of tunnel sections. The visibility and CO/VI detectors monitor the atmospheric visibility inside and outside the tunnel. the programmable logic controllers (PLCs) collect traffic and environmental sensor data and perform a diagnostic of the lighting system.

3.4. Lighting Installation Rules

Luminance requirements for different portal type tunnels are different; thus, the corresponding lighting installation rules and luminaire amounts of the lighting system are different, as illustrated in Figure 7. Table 6 lists the initial installation costs for tunnels. From this data, it can be observed that the initial installation costs increase with tunnel length. This is because the amount of equipment (e.g., LED luminaires, luminance controller, surveillance camera) increases with tunnel length.

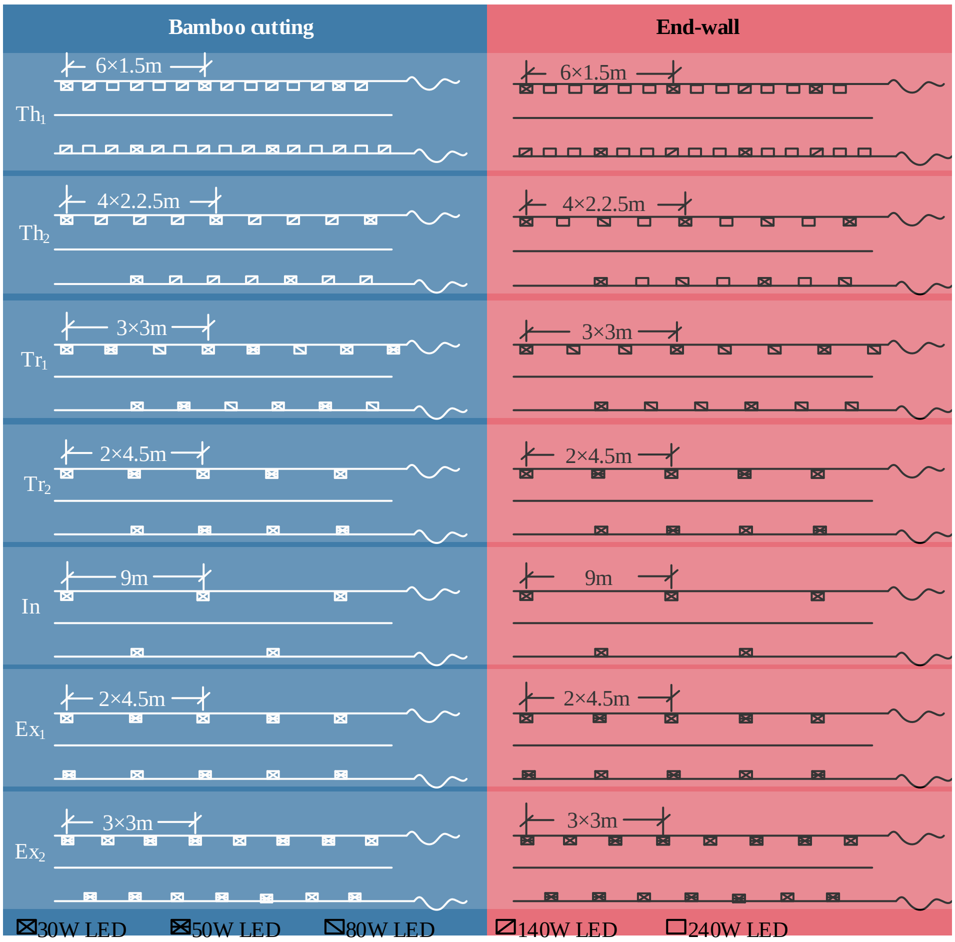


Figure 7. Lamps' installation rules for study tunnels.

Table 6. Details of initial installation costs for road tunnel lighting systems.

Device \ Tunnel Portal Type		Quantity: End-Wall	Quantity: Bamboo Cutting	Cost Per Unit/$
LED lamps	30 W	floor ((L − 315 m) × 2/9)		41.78
	50 W	43	59	47.97
	80 W	42	16	69.64
	140 W	11	62	95.95
	240 W	62	21	123.8
Local optical transceiver		1		1121.87
Remote optical transceiver		ceil (L/1000 m) + 7		1060.08
Server		1		3961.74
Local dimming controller		1		1315.42
Remote dimming controller		ceil (L/1000 m) + 7		1005.91
Luminance meter		1		1857.07
Infrared sensor		2		79.7
Microwave detector		2		162.03
Surveillance camera		ceil (L/150 m)		558.2

4. Results

4.1. Installation Costs of Different Lighting Control Strategies

According to the data from Table 5, the initial installation costs of road tunnel lighting systems with different portal types are summarized in Table 7.

Table 7. Initial installation costs of tunnel lighting systems for various control strategies.

Lighting CS	Installation Costs/$	Tunnel Type
LCL	24,003 + 41.78 ((L − 315 m) × 2/9) + 1060 ceil (L/1000 m)	Bamboo cutting tunnel
	25,228 + 41.78 floor ((L − 315 m) × 2/9) + 1060 ceil (L/1000 m)	End-wall tunnel
TSCS	36,321 + 41.78 floor ((L − 315 m) × 2/9) + 2066 ceil (L/1000 m)	Bamboo cutting tunnel
	37,547 + 41.78 floor ((L − 315 m) × 2/9) + 2066 ceil (L/1000 m,	End-wall tunnel
DACS	38,178 + 41.78 floor ((L − 315 m) × 2/9) + 2066 ceil (L/1000 m)	Bamboo cutting tunnel
	39,404 + 41.78 floor ((L − 315 m) × 2/9) + 2066 ceil (L/1000 m)	End-wall tunnel
ICS	39,220 + 41.78 floor ((L − 315 m) × 2/9) + 558 ceil (L/150 m) + 2066 ceil (L/1000 m)	Bamboo cutting tunnel
	40,446 + 41.78 floor ((L − 315 m) × 2/9) + 558 ceil (L/150 m) + 2066 ceil (L/1000 m)	End-wall tunnel

The results show that the initial installation costs for the ICS strategy are more expensive than the other three strategies because of the additional equipment (such as vehicle detectors and surveillance cameras). Moreover, the larger the tunnel length, the higher the lighting system's installation costs for all lighting control strategies. The latter is because of the increasing number of luminaires. The costs presented are based on small-quantity orders and they may decrease for larger-quantity orders. Also, the end-wall type tunnel's hardware cost is slightly more expensive than that of the bamboo cutting tunnel.

4.2. Tunnel Length Impact on Energy Consumption

To evaluate the impact of tunnel length on energy consumption for different lighting control strategies, electrical costs per day under different traffic intensities were estimated using 100-day data for each of the eleven tunnels. The relationships between daily electricity costs and tunnel lengths for different control strategies are shown in Figure 8. The fitting equations for daily electricity cost versus tunnel length for the LCL, TSCS, and DACS strategies are shown in Equations (1)–(3), respectively.

$$E_{EC\_LCL} = 696.0254 + 0.0984L \quad (1)$$

$$E_{EC\_TSCS} = 487.2178 + 0.0689L \quad (2)$$

$$E_{EC\_DACS} = 374.5777 + 0.0529L \quad (3)$$

where E_{EC_LCL}, E_{EC_TSCS}, and E_{EC_DACS} are the daily electricity cost of the lighting system for the LCL, TSCS, and DACS strategies, respectively (kWh). The coefficient of determination R^2 is 0.9955, which means the reliability of the equation is acceptable.

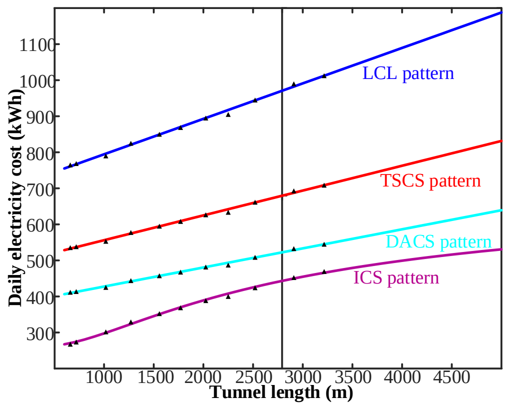


Figure 8. Energy consumption versus tunnel length for the four control strategies.

The relationship for daily electricity cost versus tunnel length for the ICS strategy had a better fitting equation using an exponential function, which is shown in Equation (4).

$$E_{\text{EC\_ICS}} = 259.96 + 211.49e^{-(\frac{100}{L}-0.03)/0.0405} \quad (4)$$

where $E_{\text{EC\_ICS}}$ is the daily electricity cost of the lighting system for the ICS strategy (kWh).

The coefficient of determination R^2 is 0.99682, which means the reliability of the fitting equation, is acceptable. The results demonstrate that daily consumption increases with tunnel length.

Data in Figure 8 show that the daily electricity costs increase with tunnel length for all lighting control strategies. The results also show that the ICS tunnel lighting system's energy consumption is consistently lower compared to the other three control strategies. This indicates that the ICS control strategy has the most significant energy savings potential.

4.3. Traffic Volume Impact on Energy Consumption

The analysis in Section 2 demonstrated that the traffic volume does not affect the electrical costs of the tunnel lighting system for the LCL, TSCS, and DACS strategies but it does for the ICS strategy.

Figure 9 shows the electrical costs of a tunnel lighting system as a function of traffic volume and tunnel length for the ICS strategy. The relationship for daily electricity cost versus tunnel length (L) and traffic volume (N) for the ICS strategy has a better fitting equation using a logarithmic function, which is shown in Equation (5).

$$E_{\text{EC\_ICS}} = -2182 - 365.8169 \ln L + 885.3517 \ln N + 41.24 \ln^2 L - 15.32 \ln L \cdot \ln N - 49.19 \ln^2 N, \quad (5)$$

The coefficient of determination R^2 is 0.9833, which means the reliability of the fitting equation is acceptable. The results show that daily energy consumption increases significantly with traffic volume for light traffic, while this increase is relatively small for a heavy traffic volume.

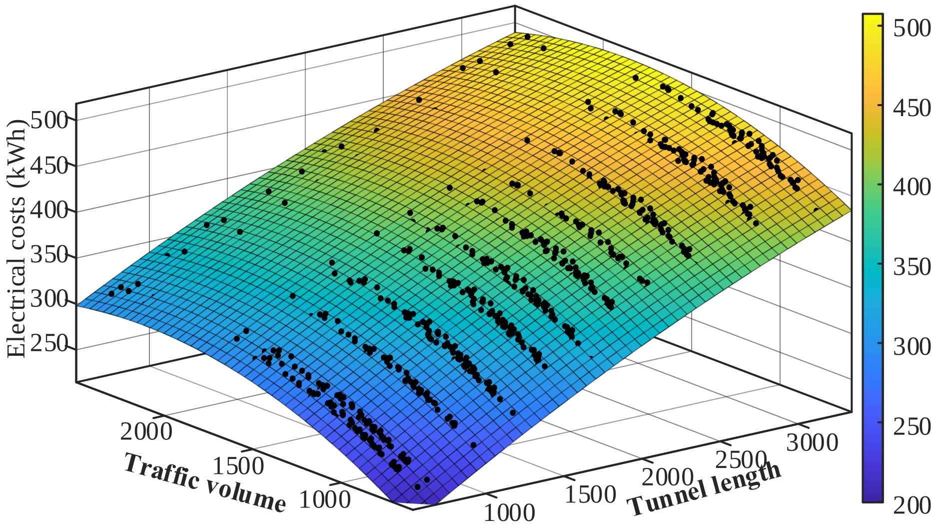


Figure 9. Electrical costs of a tunnel lighting system versus traffic volume and tunnel length for the ICS strategy.

5. Discussion and Suggestions

An optimal control strategy is obtained by minimizing the total cost of initial investment and electrical costs of tunnel lighting systems within the hardware system's lifetime.

Thus, a factor of the total cost (i.e., installation and electrical costs of tunnel lighting systems) in the case of different control strategies is being investigated as follows:

$$T_i = I_i + E_{DC\_i} \cdot r \cdot L_t, \quad (6)$$

Subscript "*i*" refers to the control strategy type, *I* is the initial installation cost (see Table 6), L_t is the lifetime of the tunnel lighting system hardware or another predetermined period (days), and *r* is the electric retail rate ($0.2/kWh).

The results showed that for L_t equal to or less than 218 days, the Q_{LCL} is smaller than Q_{DACS}, Q_{TSCS}, and Q_{ICS}. This indicates that the LCL strategy lighting system consumes the least energy, and hence, it is the most suitable control strategy for a tunnel lighting system if L_t is less than 218 days. Also, for L_t equal to or greater than 955 days, Q_{ICS} is always smaller than Q_{LCL}, Q_{DACS}, and Q_{TSCS}, which indicates that the ICS is the most suitable control strategy for this L_t range. For L_t between 219 and 954, the most suitable control strategy varies with tunnel length and traffic volume. Figure 10 illustrates the suitable control strategies for various L_t lengths (365 days, 730 days, 800 days, and 900 days) as a function of different tunnel lengths and traffic volumes. The DACS strategy has better energy efficiency in the blue-color area in Figure 10, whereas the ICS strategy has better energy efficiency in the red-color area.

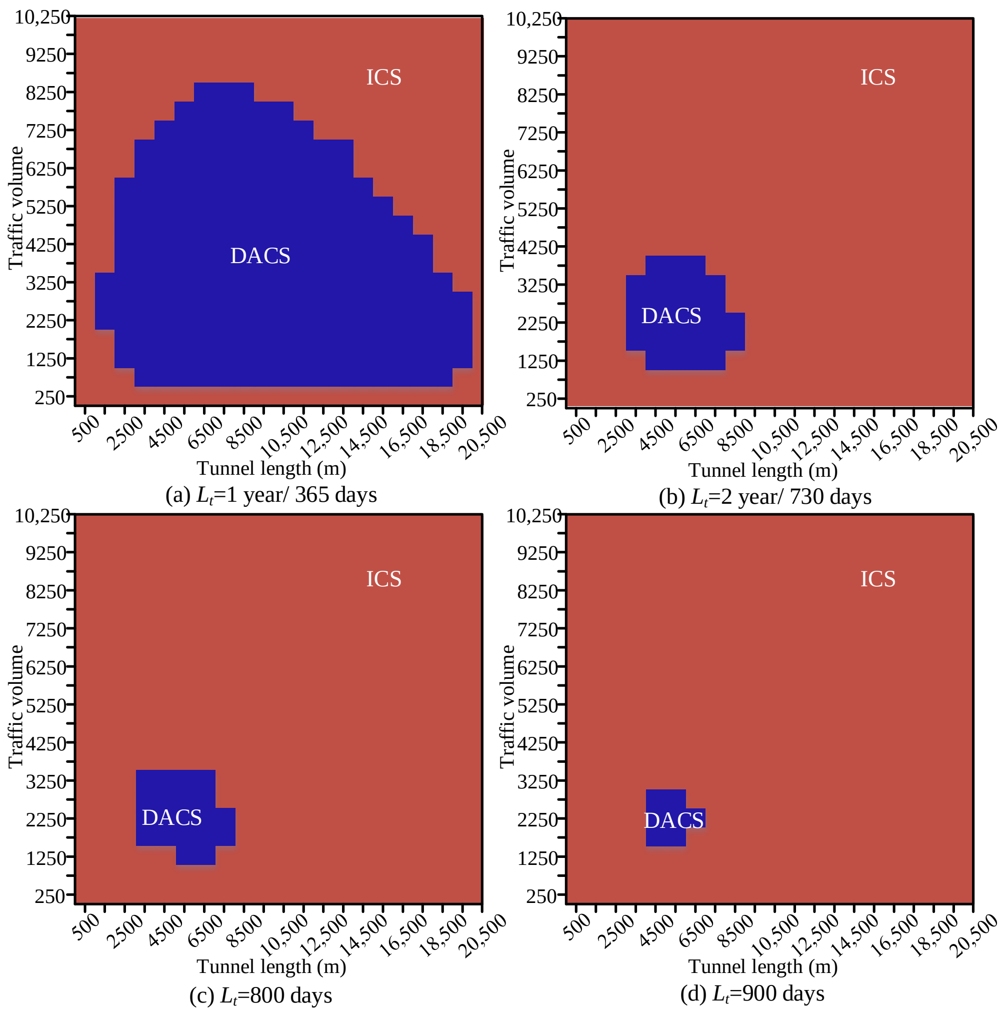


Figure 10. Choice of the control strategy for tunnels with different traffic volumes and lengths.

6. Conclusions

It is essential that we decrease the electrical power consumed by the lighting installations in road tunnels, as well as the environmental and financial impact of these installations. Despite those decreases, it is absolutely essential that these strategies do not impair traffic safety. Several groups around the world are currently working on this topic and some promising strategies are step-by-step being implemented.

This study presents an evaluation and comparison of the initial installation costs and energy consumption of LED lighting systems using four tunnel lighting control strategies, a mix of traditional and intelligent. The assessment takes into account 100-day data collected in eleven tunnels in the Jilin Province, China with tunnel lengths between 650 m and 3200 m and traffic volumes between 750 and 2500.

According to the results presented in this work, from a financial point of view, the tunnel length has a direct impact on the initial investment costs as well as the electrical costs; in return, the quantities of light sources, dimming controllers, optical transceivers, surveillance cameras, wiring, and auxiliary electrical devices (switches, transformers, etc.) increased with the increasing of tunnel length.

For each control strategy, the energy consumption was estimated utilizing unit prices used by Chinese road agencies. The comparison between the initial installation costs demonstrated that the tunnel lighting system's cost for the ICS strategy is higher than those for the other three strategies. This is because of the increasing amount of equipment (e.g., LED luminaires, vehicle detectors, and surveillance cameras). Another important finding showed that the lighting consumption of the tunnel lighting system for the ICS strategy is lower than those for the other three strategies. This is because the operating time of the lamp is reduced as the luminance is controlled based on real-time environment luminance and vehicle presence.

From the data presented in this study, in order to reduce the energy consumption and the environmental impact, it seems necessary to:

- Replace the traditional lighting fixtures with high luminous-efficacy luminaires, in order to reduce energy consumption.
- Adopt the LCL control strategy in the case of a lighting system service lifetime equal to or shorter than 218 days, in which the summary of initial investment cost and electrical costs is minimal, which is the most economical option.
- Adopt the ICS control strategy in the case of a lighting system service lifetime equal to or longer than 955 days, in which the summary of initial investment cost and electrical costs is minimal, which is the most economical option.
- Adopt an optimal control strategy between the DACS or ICS depending on tunnel length and traffic volume, in the case of a lighting system service lifetime between 218 and 955 days.
- For newly-built tunnels that have relatively low levels of traffic, adopt the ICS pattern, which could minimize electric energy consumption, and in turn, contribute more to economic benefits.
- For short tunnels, adopting the ICS pattern saves more energy than other control strategies. Thus, dividing newly-built long/extra-long tunnels into several short sections to adjust the luminance can achieve a more energy-saving effect.
- In practice, several lighting control strategies could be combined to achieve the proposed energy saving according to the tunnel area segmentation/different time periods.

In general, this study points out the optimum economical solutions for new tunnel constructions and retrofitting of existing tunnels.

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