ROAD TUNNEL MAINTENANCE IN WINTER CONDITIONS - A SOLUTION TO ECONOMIC CONSTRAINTS AND SUSTAINABLE DEVELOPMENT

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ABSTRACT

Maintenance plays an important role on the quantity of luminaires installed and operating both day and night in road tunnels. The range of values taken from ANSI/IES RP-22-11 or CIE-088:2004 for maintenance varies according to different parameters, including the lamp survival factor (LFS). In Nordic countries, environmental conditions are certainly the most important factor to consider in maintenance, due to abrasives, such as salt and calcium, that are brought into tunnels by vehicles; these abrasives accelerate lumen degradation.

Light levels vary over time due to degradation of lamp output and dirt accumulation, which obstruct the luminous flux to reach the pavement. Depending on the cleaning cycle, tunnels are over-illuminated in order to comply with recommended practices.

The black hole effect at the tunnel entrance is also more difficult to reduce during winter: there are faster and more frequent lumen variations due to snow, wet pavement and light reflections at the tunnels' portals.

Over-illumination becomes a major concern in a context of budgetary constraints and sustainable development. New technologies are now available to read and control lumen output inside the tunnel and meet recommended practices. As opposed to traditional systems, in which general purpose digital outputs are used to control a group of luminaires, Intelligent Lighting Control Systems (ILCS) use the latest available technologies to individually control and monitor every luminaire. With advanced systems, it is possible to dynamically adjust the luminaires—without over-illuminating the tunnel—by reading the real luminance levels inside the tunnel.

Individually controlling each luminaire also offers the possibility to program multiple lighting scenarios and alternate luminaires. Knowing that some luminaires are always on, the use of lamp alternation will average out lamp usage, have an impact on the lamp survival factor (LSF), and extend the relamping cycle up to four times longer.

Using a dynamic control system, combined with the use of illuminance cameras, an advanced system can adjust the light levels to actual needs, bringing very important energy savings all year long and even requiring less frequent cleaning and maintenance. Lamp alternation averages out lamps' lifetime, significantly extend the relamping cycle, which will bring major savings in tunnel operational costs. To conclude, the ILCS for tunnels helps reduce costs of operating tunnels during the winter—a period in which budgetary constraints are the most important. The ILCS reduces costs in three different ways: energy savings,, extending cleaning and maintenance periods, and extending the relamping cycle.

1. CHALLENGES IN WINTER TUNNEL OPERATIONS

The CIE-088 [1] and IES RP-22 [2] put forth recommendations concerning the daytime and nighttime lighting of tunnels and road underpasses. They include measures to be taken into consideration in order to adapt lighting to the fluctuations in external lighting. They actually recommend values of the luminance in the different tunnel zones according to tunnel characteristics, such as tunnel roadway, walls and ceiling, area surrounding the tunnel portal, and atmospheric and environmental conditions. Winter is a period where these characteristics vary from day to day and from hour to hour. There is indeed significant impact due to the season's atmospheric changes and abrasives, such as salt and calcium, that are brought into tunnels by vehicles; these abrasives accelerate lumen degradation.

Even if the order may vary from one operator to another, energy savings, maintenance, and security are the most important concerns for tunnel operators.

a) Energy consumption is an important cost of tunnel operations. As opposed to most of the other systems in tunnels, more energy is spent in lighting tunnels during the day, particularly on sunny days. Except for tunnels over 3 km long, lighting is the most energy consuming system.

   The table below describes the impact of various sub-systems and the cost impact in tunnels. It is clear that lighting is the sub-system that requires the most energy in tunnels of less than 3 000 m. A good lighting strategy is the key to reducing the load lighting brings and a viable solution that will bring important savings in tunnel operations.

Table 1

Relative influence of energy consumption with equipment type and tunnel length [3]

Length of tunnel	L ≤ 500 m	500 m < L ≤ 3 000 m		L > 3 000 m	
System / Tube	Uni and Bi	Uni	Bi	Uni	Bi
Lighting	Very high	High	Medium	Medium	Small
Ventilation	N.A.	Very small	Medium	Small	High
Safety equipment	Very small	Small	Small	Medium	Medium
Pumps	Small	Small	Small	Small	Small
Auxiliaries	Very small	Small	Small	Medium	Medium

b) Maintenance is quite a challenge in winter. Equipment must operate correctly at all times for the safety and comfort of road users as well as the people working in it. It also prevents any unplanned tunnel or lane closures. As the repair and replacement of tunnel equipment are costly, effective and preventive maintenance is the best way of preserving the value of tunnel equipment.

c) After several tragic accidents in road tunnel during the last decade, security has been one of the main concerns of PIARC TC-3.3 on tunnel operations. In 2012, this committee published a series of recommendations [4] and developed a five-step program to improve the safety in new and existing tunnels:

- Step 1: "Establish a safety framework" to confirm or prescribe the regulatory framework applicable to the existing tunnel in terms of safety. Safety objectives are defined at this stage.
- Step 2: "Investigate current conditions" to obtain a clear view of the current situation.
- Step 3: "Evaluate current tunnel safety level" in order to determine the existing level of tunnel safety.
- Step 4: "Define a safety improvement program" specific to the existing tunnel and focussed on the deficiencies identified in previous steps.
- Step 5: "Evaluate future tunnel safety level" after the work is completed to demonstrate the safety benefits obtained through refurbishment.

Today, hundreds of tunnels around the world are going through refurbishment. However, the type of lighting control system to install remains questioned by many operators.

The three aforementioned challenges become even more significant during winter operations, when snowy and wet road surfaces affect the luminance at tunnels' portals.

A recent paper published by the Aalto University School of Science and Technology [5] indicated that "on major roads there is usually not much snow because of the traffic, salting, and snow clearance. However, the road surroundings are usually covered with snow, which increases the overall brightness of nighttime driving conditions" They found that the average road surface luminance of slightly snowy surfaces were 30 to 50% higher compared with dry road surface conditions.

Understanding that variable weather conditions have a more important impact on the surface roads during winter, it is more difficult to maintain a good quality of lighting.
This also has a direct impact on security, since the uniformity of road surface luminance is low and the reflection on wet road surfaces can affect a driver's vision.

Inside the tunnel, conditions during winter are the opposite. The dirt caused by abrasives, such as salt and sand, inside the tunnel (on walls and luminaires) will significantly reduce the luminance inside the tunnel. Higher luminance at the tunnel portal and reduced luminance inside the tunnel cause an even more important—and potentially dangerous—black hole effect in the tunnel.

For both situations, the solution implemented by most operators is to set up the system for the worst case scenario—both at the portal entrance and inside the tunnel—by increasing the lumen levels even when not necessary. Because of a lack of accuracy on lumen levels, this causes a substantial waste of energy. This same study states that "it has been estimated that in northern and in northeastern Finland, for 50 to75% of the total burning hours, road conditions are snowy or at least the road surroundings are covered with snow.

Winter conditions also bring other types of hazardous conditions. Electrical and mechanical systems must be reliable to avoid failure and cause safety problems. Any preventive maintenance and remote tunnel monitoring will help in preventing failures and proactive interventions.

The type of lighting control system becomes even more important to ensure the right level of lumens, optimal maintenance, and increased safety.

2. STANDARD CONTROL SYSTEMS

2.1. Description

A Programmable Logic Controller (PLC) System is used to control tunnel lighting systems. Each system is normally custom-made for each particular tunnel and offers limited features in comparison with more technologically advanced systems.

In a PLC System, general-purpose digital outputs are used to control power contactors that are installed in the electrical (DB) cabinet. The contactor, or relay, then controls the lamps that are pre-wired according to pre-defined lighting stage scenarios that were calculated during the design phase. Figure 1 below shows the general arrangement for a three-light level system.

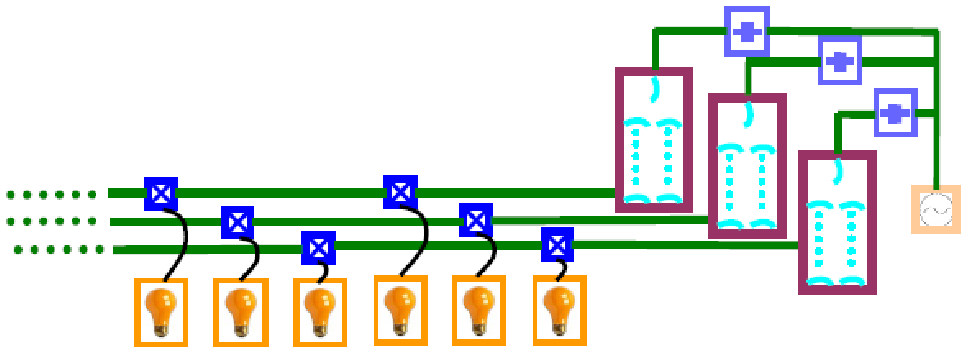

Figure 1
Tunnel lighting control system diagram

2.2. Problems and Limitations

2.2.1. Energy

Because the PLC System has a rigid hardwired structure, every luminaire assigned to a lighting stage will have one cable connected to a contactor that controls it. This situation technically limits the possible number of lighting stages and is not necessarily economical for tunnel operators. To make sure operators meet various lighting security recommendations, most tunnels around the world are over-lighted due to the limited number of lighting stages.

Figure 2 shows the various stages inside the tunnel to match the CIE luminance curve. For practical purposes and budget optimization, the number of stages is usually limited to four or five. If the number of stages is increased, the lumens' measurements will be more precise; it will therefore be possible to identify potential energy savings. This can be achieved by having the proper data to simulate lighting levels and duration.

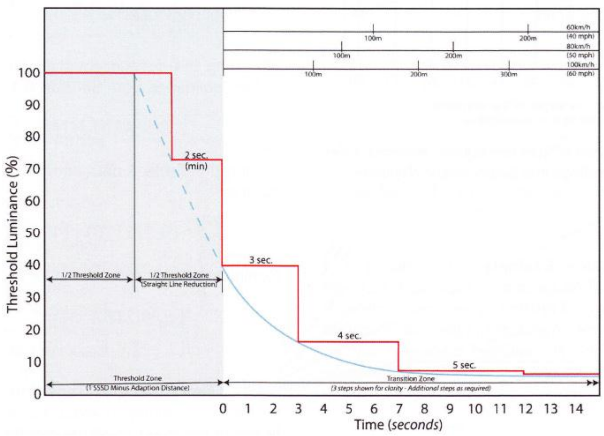

Figure 2

Recommended luminance reduction for thresholds and transition zones [1]

2.2.2. Maintenance

The PLC System does not offer maintenance management information and controls, such as lamp failure, burn hour usage, etc. This lack of vital information can cause increases in maintenance costs for the operator, who cannot optimize the number of tunnel interventions.

The US Department of Transportation [6] suggests to "verify proper operation of the lighting fixtures in the tunnel, the counting and report of lights out on night and day lighting and to replace any inoperable bulbs or ballasts with similar or increased efficiency" once a month. This means that operators don't really know the status of the lighting systems between inspections. Moreover, this implies sending maintenance people to monitor luminaires manually. If maintenance or repair is also performed, this results in tunnel or lane closures.

2.2.3. Communication

The PLC System offers very limited interfacing capabilities with the Integrated Traffic and Plant Management System (also called ITPMS); the system provides simple information on lighting stages and basic status reports. With a basic system, no remote access to luminaire status is available.

2.2.4. Precision

Most of the time, the PLC System is limited to 3 or 4 lighting stages; it can therefore never adapt to real outside lumens at the tunnel portal, which would provide the ideal conditions to ensure the comfort and safety of drivers and reduce energy costs.

3. ADVANCED SYSTEMS

As opposed to the traditional PLC system, in which general purpose digital outputs are used to control a group of luminaires, the ILCS individually controls and monitors every luminaire. Using power electronic components instead of simple electric ones, it is possible to more precisely and dynamically adjust the luminaires, alternate lamp use, obtain lamp protection features, monitor electrical parameters, and add different features that will help save on both energy and operational costs.

3.1. Energy Savings

As indicated in IEC-088, it is necessary to provide lighting control in the threshold and transition zones of the tunnel as the luminance levels are constant percentages of the access zone's luminance. When screened daylight is used for the entrance zone lighting, the control is automatic. It should be noted, however, that depending on the transmission characteristics of the screens, the luminance under the screens is not always linearly correlated to outdoor light levels. For artificial lighting, a system that provides more precise control is needed. The control may be managed through continuously dimming devices or by switching lamps in separate steps. For adequate light control, the access zone's light levels must be continuously monitored.

3.1.1. Number of Lighting Stages

By individually controlling luminaires, lighting stages can increased from 3 or 4 to 10 or 12. This dynamically adapts a lumen lighting level to the one at the tunnel portal as well as to the one recommended by the different standards (American and European standards for tunnel lighting).

This technique reduces over-lighting—all while using the right amount of energy to lighten the tunnel and maintaining user safety.

3.1.2. Dirt and Depreciation Factors

In order to ensure that they meet lighting requirements, tunnel operators using conventional systems have to plan for worst-case scenarios when it comes to photometry inside the tunnel. Whatever the length of the cleaning cycle, tunnels are always over-lighted from the beginning to almost the day before the planned cleaning maintenance. Over-lighting is required to make sure that the lumen levels are appropriate when the luminaires are dirty.

The lumen maintenance strategy will use the lamp replacement cycle and cleaning of luminaires to readjust light levels. A number of variables, such as temperature, luminaire deterioration, room surface dirt accumulation, lamp burn out, and others, will influence luminance values. The global value can range from 0.3 to 0.65. The goal is to determine what factors will apply and how this strategy influences readings. The formula to calculate the Total Maintenance Factor (TMF) is:

- TMF = LLD x LB x LDD x EF

From the aforementioned figure and table, we can certainly recognize that the main factors used for defining TMF are:

- LLD (Lamp Lumen Depreciation or maintenance)
- LB (Lamp Burnout)
- LDD (Luminaire Dirt Depreciation) is a value picked in between cleaning of luminaire.
- EF (Equipment Factor) is not time- sensitive. It reflects line voltage variations, ballast and lamp factors, and sometimes the ambient temperature.

The most influencing factor is the LDD, which accounts for almost 50% of the TMF and maintenance cycle.

The lumen maintenance strategy is used in conjunction with the dimming system, since the fine-tuning of light levels is easier. With dynamic lumen adjustment, the ILCS has a very good control over the LLD by using the monitoring function of the control unit in the luminaires.

For the LDD, measurement devices with an algorithm need to be developed to simulate dirt deterioration.

The use of a luminance meter will read the real lumens. The controller will dynamically adjust and control light levels when the luminaires get dirty. A calibration process should be defined in order to compensate for the lack of precision in the measurements taken.

The ILCS offer a dynamic adjustment of luminance according to the real dirtiness of the luminaires, avoiding over-lighting between cleaning maintenance periods. This results in better lighting and significant energy savings.

3.1.3. Traffic Speed

One of the most important factors in tunnel lighting is speed. The lighting design is usually calculated at a set design speed. In practice, road and tunnel designs are such that speed and flow are usually interrelated, as a high design speed is selected for roads for which a high flow is expected. High speeds require better visibility and therefore generally a higher luminance level.

Table 2 of RP-22 gives the luminance level in threshold zone. This gives the luminance level in the interior zone. From these tables, we can define a ratio of reduction of luminance for various speeds.

Table 2

Light reduction ratio for speed variation in tunnel [1]

Actual speed (km/h)	Reduction ratio for 100 km/h for threshold	Reduction ratio for 100 km/h for interior zone
80	0.89	0.8
60	0.71	0.6

This energy saving strategy is based on the flow of traffic at the entry of the tunnel, where a monitoring system tracks speed and feeds it to the TLCS, which adjusts light levels accordingly. Various types of sensors, such as loop detection, Road Transport Management System (RTMS), lasers, or others, can be used and are linked to the master control system to adjust light according to traffic speeds. The CIE curve then needs to be adjusted for the transition zone. A pre-programmed algorithm will check values in a table to select circuits and luminaires to be turned on or off.

3.2. Operational and Maintenance

3.2.1. Extending the Relamping Cycle

Whatever the type of lamp operators uses, relamping is a very costly operation. Due to the cost of manpower, moving equipment, and closing lanes and tunnels, most operators will change all the lamps in the tunnel when strategic lamps are at the end of their useful life.

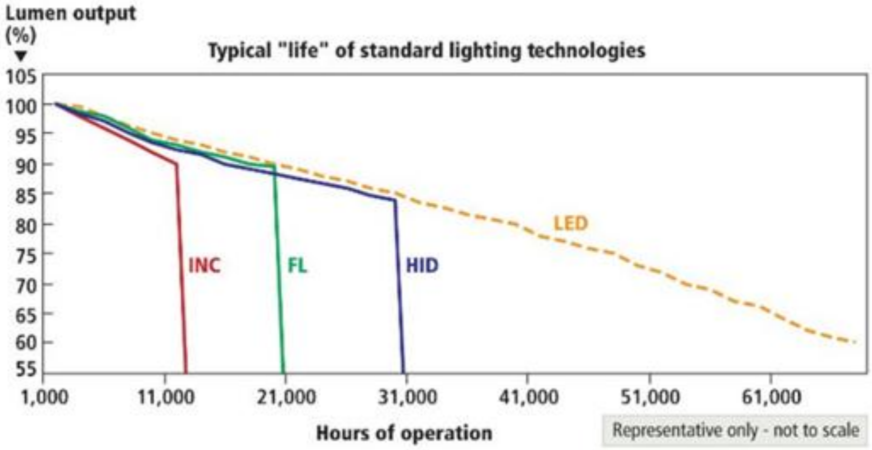

Figure 3

Lumen degradation and failure behaviour for incandescent (INC), fluorescent (FL), high-density discharge (HID) and LED lamps [7].

a) Dynamic Lamp Alternation

The optimal use of luminaires increases their useful life, decreasing replacement costs in three main ways:

- The addressable control system enables the dynamic control of the lamps in order to avoid over-lighting; this is done by increasing the lighting stages of the lamps only when necessary.

- When the same type of lamps are installed in luminaires, the alternation of luminaires from one stage to the other will extend the lamps' useful live and average out their aging. When relamping is required, lamps will have been used more equally and much closer to their full potential.

- Firmware programmed in the ILCS will include different activation delays (mainly for HID luminaires) that will prevent lamp over-use.

3.2.2. Reduce Maintenance Operations

a) Takeover Lamp Alternation

Intelligent lamp alternation (failure takeover) in intelligent system orders an automatic action when there is a lamp failure; an adjacent alternative luminaire will take over with respect to the photometry. An alarm can still be sent to the maintenance team; however, no immediate intervention will be required.

b) Remote Status Monitoring

Whether intelligently using power line or twisted pair cabling, bidirectional communication offers the possibility to remotely monitor and perform a detailed analysis of the electrical parameters, such as voltage, power factor, current, lamp status, etc.

c) Preventive Maintenance Programs

Remote access to information related to the lamp status and different electrical parameters are the key to the designing a preventive maintenance program. Such a program can help to increase the reliability of a lighting system and reduce the number of interventions in the tunnel by optimizing the number of resources dedicated to maintenance.

Different alarms and maintenance reports bring a better planning of required interventions, replacement equipment, and procurement according to real needs. Moreover, they help to reduce the capital cost of unnecessary inventory and storage costs.

With access to such comprehensive information, operators can design preventive maintenance programs to include the following (even before entering in the tunnel):

- Failure diagnostics
- Lamp lifetime usage
- List of equipment to replace
- Alarms (procurement, failure with or without immediate intervention, etc.)
- Maintenance routes
- Etc.

3.2.3. Communication

By effectively controlling and monitoring lighting in tunnels, the ILCS provides digital data to operators that can be turned into strategic information for overall operations. Main controllers usually have a web-based interface to enable remote access to the aforementioned data. Information can also be accessed by the higher control system or a dedicated Human Machine Interface (HMI).

A HMI can be accessed locally and/or remotely. This type of interface includes security login, system settings and configuration, system overview, camera overview, etc. In addition, the HMI can help operators monitor and control lighting, in real time, for an optimal tunnel lighting system operation.

3.3. Safety

With the high number of possible lighting stages and ability to dynamically change lighting levels based on different environmental conditions, the ILCS will provide more accurate lighting levels that will enhance drivers' comfort and vision—and ultimately improve safety.

4. SOLUTION

Operating a tunnel in Nordic countries brings more important challenges than in other countries. The choice of an ILCS can be part of the solution to improve safety as well as save on energy and maintenance costs.

Standard systems do not have the accuracy and flexibility to be fully efficient in winter conditions. The ILCS brings a more accurate lighting both inside the tunnel and at the tunnel portal. It adjusts the lumens according to the variable conditions in winter.

The quality of tunnel entrance lighting varies more frequently during winter depending on snow accumulation and in conjunction with other weather conditions that impact the real lumens at the tunnel portal. A dynamic system with multiple lighting stages will ensure that the tunnel portal will offer the appropriate visual conditions and meet the recommendations for the best possible safety—without over-lighting and wasting energy.

The ILCS also offers different features to help in preventive maintenance. Remote access of the lighting system can report the real-time status of the lighting system and include strategic information that can help to perform failure diagnostics. Maintenance teams can then get into the tunnel only when needed and with the right equipment to maintain the system.

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