The Waterval Boven tunnel (previously the NZASM tunnel) lies just outside Waterval Boven on the N4. Trans African Concessions (TRAC), the operator of the N4 toll route between Pretoria and Nelspruit, is upgrading this route. TRAC focused its attention on the tunnel.

A study on tunnel lighting

The old installation
The original lighting system in the tunnel consisted of 40 floodlight luminaires (20 on each side) providing indirect lighting to the carriageway surface. The mounting height of these luminaires was 4.7 m. They were mounted in the inverted position directing all the light flux against the roof. Due to its condition the roof has a very poor reflective factor (between 10-30%). The 40 luminaires each contained a 400 W high pressure sodium (HPS) lamp. The total load was therefore 17.3 kW and electricity consumption was estimated at R3 500 a month. Of the 40 luminaires, one was lost through theft and another was not functioning. An insulated single-phase cable with a core size of about 4 mm² was strung on a catenary steel wire connecting the luminaires on each side of the tunnel.

Problems
The average lux level in the tunnel was about 8.6 lux measured horizontally on the carriageway surface. For this class of road entering the tunnel (A2: Major roads for speed limits not exceeding 90 km/h) the average lux level should be 20 lux (600 cars/Ln/hr). The indirect lighting technique can only be effective if the reflective surface has an adequate light reflective factor or property. In this case the reflective factor of the roof was very poor. The system was, therefore, grossly inefficient in terms of average lux/Rand/day.

Current system - R3500/month electricity consumption
Average lux = 8.6 lux
Rand/day = 3500/30 = R116/day
Average lux/Rand/day = 8.6/116 = 0.074 (poor)

Possible new system - R560/month electricity consumption
Average lux = 24 lux
Rand/day = 560/30 = R19/day
Average lux/Rand/day = 24/19 = 1.26 (excellent)

The cable supplying the luminaires is too thin, with the following results. The voltage at the luminaire at the end of the cable is 183 V, which is a voltage drop of 20.4%. Normally the maximum permissible voltage drop is 10%. The effect of this is higher I²R losses as well as a dimmer lamp. The fault level at the end of the cable is about five times lower than it should be and will, with many types of short circuits, not produce a high enough fault current to operate the protective circuit breaker. Such an event will destroy the cable and cause a fire or explosion if a combustible material is close by. The luminaires are mounted face up and thus collect dust and dirt much quicker than would be the case if they were mounted face down. A positive aspect of the current installation is the ease with which the luminaires can be reached for maintenance. From these points it is clear that the existing lighting system is unsatisfactory. A decision was made to upgrade the lighting in the tunnel to A2 standards.

Tunnel luminaire requirements
The client wanted luminaires that were robust, corrosion proof and with a good IP rating as the tunnel was generally damp inside. They should also have an excellent LOR and symmetrical photometric performance to illuminate the tunnel to A2 standards with the lowest number of luminaires (budget constraints). The lamps should have an extremely long lifetime as the new luminaires would be positioned in the centre of the roof of the tunnel, making access for maintenance difficult. The writer proposed the BEKA Endura luminaire fitted with an Osram 150 W Endura induction lamp (see Fig. 1).

The system offers the following advantages.
- Infrequent lamp and electronic control gear (ECG) replacement - expected lifetime of 60 000 hours. In a tunnel that means approximately 6.5 years before maintenance is required.
- High light output – 80 lm/W - therefore lower energy costs and fewer units required
- Very small variations in luminous flux over temperature range and lifetime
- Non-flickering effect

Fig. 1: The Bekatec Endura tunnel luminaire.
• No stroboscopic effect
• Very good colour rendering
• High resistance to switching
• Instant flicker free start and re-ignition
• Fast run up to full luminous flux
• Reliable ignition at low temperatures
• Low profile, thus suitable for very flat luminaires
• Low cost reflector design because of straight lamp construction allowing simple bending of reflector sheet
• Free burning position
• Larger distance allowed between ECG and lamp

The reflector and luminaire details

The luminaires should be constructed in such a way that the full advantages of the Endura system can be optimised. The requirements for the Endura luminaire are generally the same as for the luminaires designed for other lamps, but there are a few aspects that are important. The reflector system should give high optical efficiency and reduce retro reflection; the thermal behaviour of the lamp should be optimal; the thermal behaviour of ECG should also be considered; and there should be shielding against electromagnetic interference.

The reflector system

In a fixture intended for high bay or tunnel lighting applications, it is important to direct as much light downwards as possible. Therefore a reflector is incorporated within the fixture that redirects light from the upper surface of the lamp so that it travels in a downward direction. Osram has very definite recommendations for the reflector contour and in Fig. 2 it is illustrated how a light ray emanating tangentially from a point E on the lamp surface and striking the reflector at point D, is reflected back upon itself and this condition is satisfied for all other points of the reflector contour ψ(r/R).

In this way it is possible to suppress the light loss due to scattering and/or absorption. Thus, still referring to Fig. 2, the reflector curve can be determined by the following formula:

$$\psi = \psi_o \pm \{[(r/R)^2 - 1]^{1/2} + \cos^{-1}(R/r)\}$$

where \(\psi_o = 0\) and the positive bracketed factor, +\{\ldots\}, is a spiral contour that issues radially from the lamp surface and unfolds clockwise. Similarly, for the negative bracketed factor, a counterclockwise opening spiral unfolds with the curves starting at any angle \(\psi_o\).

Eventually the final recommended reflector system looks like that shown in Fig. 3. When comparing it with the reflector system of the luminaire proposed for the tunnel (Fig. 4) one can see that it is very similar and gives good results with an efficiency of 86%.

Measures taken against thermal behaviour of ECG

The operational lifetime of the Endura system is not really determined by the lamp, but mainly by the ECG. It is generally considered that the life expectancy of electronic components drops by about half for every increase of 10°C in temperature. For this reason it is vital that the ECG is kept under the defined temperature limit of 70°C during the whole operational period of the luminaire, even under extreme conditions. Thus, the ECG should be kept as cool as possible, and positioned in the coolest part of the fixture. With the offered tunnel luminaire, this was achieved (see Fig. 5) as follows.

- A partition wall was placed between ECG and lamp compartments to diminish heat transfer
- The ECG was located in the lowest and furthest point from the lamp compartment, i.e. the coolest spot in the fixture
- The hole in the partition wall for the wiring between ECG and lamp was plugged with a special material to ensure no heat transfer from the lamp via this conduit

Measures taken against electromagnetic interference (EMI)

The international regulation CISPR 15 (EN 55015) distinguishes between line-conducted and -radiated EMI and the limits must be adhered to. The line-conducted EMI in the ECG used in the tunnel luminaire is suppressed, but in cases of inappropriate connection between input and output cables of the ECG, interference can rise above permissible levels. In the tunnel luminaire sufficient suppression was achieved by placing the input and output wires as far away from each other as possible; leading the output line as far away as possible from the grounded parts of the luminaire housing; making the main cable within the luminaire as short as possible. During installation, the contractor was instructed not to loop the distribution cable through the luminaires but rather to tee in at each luminaire so that the line-radiated EMI could be kept as low as possible.
The induced current in the discharge tube of the Endura lamp generates an additional magnetic stray field (radiated EMI) and this interference can reach critical values. A free burning lamp would radiate more strongly, as much as 80 dB, but this radiation decreases drastically when the lamp is fitted into a metal luminaire.

From a flicker effect point of view, the installation is also very comfortable. This flicker effect phenomenon is the result of light sources appearing and disappearing in the peripheral part of the driver’s vision and certain ranges of flicker can be more disturbing than others. Practically, the flicker effect is disturbing for frequencies between 2.5 Hz and 15 Hz. This frequency is determined by dividing the speed of the motorist in m/s by the spacing in m between luminaires. For the current installation in the Waterval Boven Tunnel the results are:

- Speed = 60 km/hr, i.e. 16,6 m/s
- Spacing between luminaires = 13 m
  Therefore flicker frequency = 16,6/13 = 1,3 Hz, and
- Speed = 80 km/hr, i.e. 22,22 m/s
- Spacing between luminaires = 13 m
  Therefore flicker frequency = 22,22/13 = 1,7 Hz

In both cases, this is well below the lower limit of 2.5 Hz.

**Comfort in the Waterval Boven tunnel**

The currently installed lighting system provides a very comfortable luminous environment for users of the tunnel at night. However, the question is whether these same comfort levels are also achieved during daytime. The purpose of lighting a road tunnel is to provide continuity in visual performance for motorists entering and traveling through a tunnel whether it is nighttime or daytime. When approaching a tunnel during the day, motorists are confronted with a problem of visual adaptation. Their eyes must adapt to the sudden change in lighting level from bright sunlight outside to a level of almost zero just inside the tunnel portal.

This phenomenon is known as temporal visual adaptation and the eye can only adapt to this low level of light over a relatively long period of time. The length of time corresponds to the distance covered by the driver’s vehicle, which is a function of the vehicle’s speed.

A second phenomenon that can be added to the first one is spatial adaptation. When driving normally, a driver’s field of vision is relatively wide (20 degrees of aperture), however, as he approached the tunnel this field of vision narrows to a field corresponding more or less to the aperture of the tunnel’s portal, i.e. about 2 degrees. This leads to the so called “black hole effect” which one experiences when approaching a tunnel that is badly lit during the day (see Fig. 9). From this photograph of the entrance portal of the Waterval Boven tunnel it can be seen that there is a possibility that many motorists will experience discomfort during a daytime entrance in that for a very short time and at a distance close to the tunnel entrance, they suddenly cannot see anything.

With the currently installed lighting, a computer simulation was run to visualise the black hole effect during daytime and this can be clearly seen in Fig. 10.

**Daytime lighting requirements for short tunnels**

In South Africa, it can be argued that the Waterval Boven tunnel is a short tunnel (333 m compared to the Huguenot...
tunnel at 3,913 m), that it is a straight tunnel and that the exits can be clearly seen from both entrances. Thus, why light it for daytime requirements?

However, CIE 88 gives recommendations for the lighting of short tunnels. In Fig. 11 it can be clearly seen that CIE 88 recommends that any tunnel longer than 125 m must be provided with normal threshold zone lighting levels.

The CEN technical report on tunnel lighting gives another method, which can be used to determine the necessity of lighting a short tunnel for daytime purposes. This report introduces the concept of “look-through percentage” (LTP) that is defined by the formula \( LTP = 100 \times \frac{EFGH}{ABCD} \) as shown in Fig. 12. The centre for the perspective drawing is at a point 1.2 m above the road surface; in the middle of the driving lane and taken at the required safe stopping distance (SSD).

The daylight influence shortens the visual length of the tunnel. Therefore an apparent entrance and exit portal should be used to determine the LTP. For the entrance, the apparent entrance portal is about 5 m inside the tunnel and the apparent exit portal is about 10 m inside the tunnel.

The following conclusions are listed by the CEN technical report.

- For \( LTP < 20\% \), artificial daytime lighting is always needed
- For \( LTP > 50\% \), artificial daytime lighting is never needed
- For \( 20\% < LTP < 50\% \), artificial daytime lighting is sometimes needed

If we look at Fig. 13 which shows a view of the Waterval Boven Tunnel entrances and exits, at the required safe stopping distance, and if we do the calculation for the LTP, the result is somewhere between 3% and 8%, depending on how the areas are calculated.

From the above it becomes quite clear that the Waterval Boven tunnel needs to be properly illuminated during the daytime so that when a driver approaches the tunnel during daytime he is able to detect any obstacle on the road in the tunnel and react before entering it.

Thus the lighting inside the threshold zone should be designed to ensure that obstacles could be detected at a distance from the tunnel portal that equals the safe stopping distance (SSD) at the speed limit (see Figs. 14 and 15).

**Threshold lighting for the Waterval Boven tunnel**

The luminance value at the beginning of the threshold zone must be based on the luminance levels at a distance that equals the reference SSD in the approach to the tunnel, in the driver’s conical field of view having an opening angle of 20 degrees centered on the tunnel portal. This luminance is called the access zone luminance \( L_{20} \).

The CIE 88 document gives two methods to determine the \( L_{20} \): a rough evaluation of \( L_{20} \) based on the percentage of sky visible in the 20 degree conical view, the brightness situation and the SSD, and a second method which is more accurate and allows calculating the \( L_{20} \) value from a photograph of the entrance to the tunnel.

**First Method: rough evaluation of \( L_{20} \)**

The ‘Waterval Boven tunnel entrances’ 20 degree conical views are similar to that shown in Fig. 16, and using the stopping distance diagram shown in Fig. 17. (In the 80 km/h direction, the tunnel slopes up at approximately 15%, and in the 60 km/h direction it slopes downwards at the same percentage) with the speed limits of 60 km/h (traveling to Nelspruit) and 80 km/h (traveling to Gauteng) together with the values in Table 1, the access zone luminance \( L_{20} \) is between 1500 cd/m² and 2500 cd/m².
L20 ratios given in Table 3 for different SSD and different L/Lr ratios (refer to CIE 88). The result for the Waterval Boven Tunnel gives a recommended Lth of between 75 and 90 cd/m² for a symmetrical lighting installation.

Second method: calculation of L20

This second method is much more accurate in determining the access zone luminance and allows calculating the L20 value from a photograph of the entrance of the tunnel (see Fig. 13). This photo was taken at the average stopping distance of 77.5 m.

The value of L20 is given by the formula

\[ L_{20} = \gamma L_C + \rho L_R + \varepsilon L_E + \tau L_{th} \]

Where

- L_C = sky luminance and \( \gamma \) = % of sky
- L_R = road luminance and \( \rho \) = % of road
- L_E = surrounding luminance and \( \varepsilon \) = % of surround
- L_{th} = threshold zone luminance and \( \tau \) = % of tunnel entrance

The term \( \tau L_{th} \) is normally negligible as the threshold luminance is low compared to the other luminances and the \( \tau \) percentage is also low for stopping distances greater than 60 m, thus for most situations the formula becomes

\[ L_{20} = \gamma L_C + \rho L_R + \varepsilon L_E \]

Using the photograph in Fig. 13 and estimating the values of \( \gamma \), \( \rho \), and \( \varepsilon \), the \( L_C \), \( L_R \), and \( L_E \) values can be read off Table 2.

Because the Waterval Boven tunnel runs in a North West- South East direction, the E-W values are used from Table 2. From Fig. 13, the estimated values of \( \gamma \), \( \rho \), and \( \varepsilon \), are 0%, 60% and 40% respectively. Substituting all the values into the formula gives a result of 3200 cd/m² for the value of L20. This is turn equates to a recommended threshold zone luminance \( L_{th} \) of 160 – 192 cd/m².

During a site visit to the tunnel, luminance measurements of the road, tunnel portal entrance and surrounding rocks provided the following recorded values:

- Road = 5000 cd/m²
- Portal = 1000 cd/m²
- Rocks = 200-500 cd/m²

With estimated percentages of 55% for the road, 15% for the portal and 30% for the rocks, and substituting these values into the L20 formula, a remarkably consistent value of 3050 cd/m² is calculated for L20.

This new design means that the power and electrical distribution requirements increase drastically. It also requires that the threshold and transition lighting circuits be connected to an emergency source of supply, in case of power failure. Further, proper adjustment of the tunnel lighting in the threshold zone and transition zone may have to be applied, as luminance values in the access zone vary with changes in daylight conditions. This can be achieved by mounting a luminance meter between 2 m and 5 m high on the near side of the road at the SSD from the tunnel portal considering accordingly to time of day, season and weather conditions, thus it is advisable that the worst-case value is used.

Proposed redesign of the tunnel lighting system for daytime requirements

Based on the above, the tunnel lighting has been redesigned for the higher values required for the threshold zone and transition zones, and the lighting correspondingly reduced to the value of the interior zone where the curve would roughly approximate to that shown in Fig. 15.

Now, all of a sudden, the design of the tunnel lighting system has become much more complicated and the number of luminaires has increased drastically from 25 to 271 units, with the threshold and transition lighting zones utilizing 400 W HPS symmetrical lighting fixtures.

A computer simulation was also done to see how the “black hole effect” has improved and there is no doubt that obstacles can now be clearly seen in the tunnel entrance at the required SSD (see Fig. 18).
and by linking this meter to a central microprocessor. This gathers the data needed to determine which lighting level should be used to maintain the preprogrammed luminance ratio \( k = \frac{L_\text{th}}{L_\text{20}} \) (see Table 3) by switching the luminaires in the threshold and transition zones in steps. A control building would also have to be erected from where the tunnel lighting system is controlled, monitored and maintained.

**Conclusion**

Re-designing the Waterval Boven tunnel lighting requirements for daytime conditions, as recommended in CIE 88 and the CEN technical report, results in considerable expense, which the operator of this route (TRAC) has perhaps not considered before. Whether funds would be available to finance such a lighting installation (budget figure of R2.5-million) is not known.

A new question can be asked. Is this vast cost justified just because the CIE and CEN documents recommend that this tunnel should have proper threshold lighting during the daytime? In the 32 years that this tunnel has been in operation, consensus is that there have been no accidents in this tunnel. Is this just luck, or is it perhaps for the following reasons:

- The speed limits in this tunnel are 60 km/h and 80 km/h respectively, thus at the SSD drivers are close enough to the portals to see any possible obstructions on the road surface.
- The tunnel portals are large – 13.5 m wide at road surface and 7.9 m high in the centre of the tunnel. With such a big opening there is possibly a considerable penetration of daylight into the tunnel, allowing obstructions to be seen in time to stop safely.
- The author drove through the tunnel a few times in both directions, at the speed limit, and no serious discomfort was experienced, nor could he could not see anything just inside the tunnel entrance.

Perhaps the specialists in tunnel lighting should revisit the experiences with sites like the Waterval Boven tunnel, and possibly reconsider the recommendations for short tunnels.

Or else, perhaps the operator of this tunnel (TRACS) should seriously consider revising the lighting in this tunnel to comply with CIE, and in the near future, SANS 10098-2 recommendations, which promote safety for motorists and good road and tunnel lighting practice.

**Acknowledgements**

The author wishes to acknowledge the contribution made by Steyn de Lange of VKE Consulting Engineers.

**References**


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