Daylighting of Tunnels

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Acknowledgement

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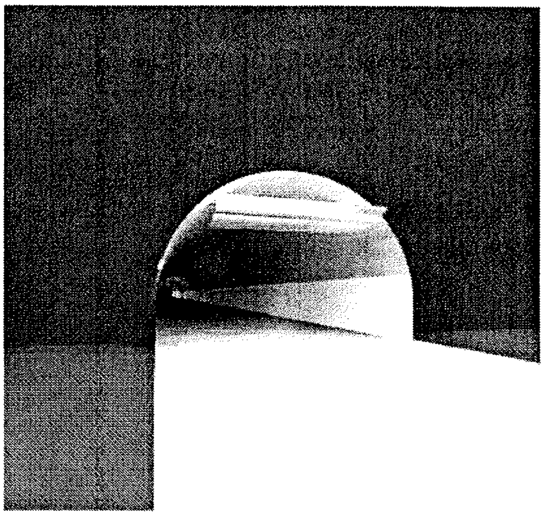
Summary

"Jonerwald" tunnel near Rapperswil



Tunnel entrance with an anidolic system (simulation model)

The aim of this study was to examine the possibility of redirecting daylight deeper into tunnels by an innovative daylight system. The redirected daylight could either replace the electric lighting in the tunnel entrance to economise electricity or be used to increase security either in artificially lit tunnels with excess traffic or in unlit tunnels.

The reasons for the project were three-fold: possible energy saving; the existence of a new technology from building physics - the anidolic system – which redirects daylight further into spaces; increased security at tunnel entrances. If the exterior daylight and especially sunlight levels are of importance then high interior luminance levels are required for adequate eye adaptation. It is exactly in such circumstances that sufficient daylight is available to be redirected by an anidolic system into the tunnel to supplement electric lighting in the tunnel entrance. The anidolic system is composed of a scoop outside the tunnel and two facing reflectors inside which create a bundle of rays directed towards the tunnel depth. From a safety point of view, the eye can adapt more easily from high luminance levels to low ones if the transition is from daylight to daylight rather than from daylight to electric lighting. Redirecting daylight therefore helps the eye to adapt to lower light levels in the tunnel entrance.

Scale models of an existing tunnel and an anidolic system were built. The daylight factors were measured inside the tunnel under the artificial skies in Lausanne for the cases with and without any anidolic system. The results of the comparisons of the measurements against the simulations (made with Radiance), were sufficiently good to proceed with the luminance simulations.

Road lighting analysis generally is based on the road luminance. A particular luminance, which is a direct function of the area weighted luminance levels of the tunnel's immediate surroundings, as seen by an oncoming driver, is required inside the tunnel entrance. A maximum exterior luminance can be defined, which then establishes the maximum required

interior luminance level for the whole tunnel entrance section. A lower level is acceptable further inside.

Two tunnel, one in the mountains and the other without any mountains above it, but both with high solar incidence, were chosen for this study. For both tunnels, the following luminance values were calculated with Radiance for all daylit hours of a given day for five selected months: the hourly exterior luminance levels of the surroundings of each tunnel; the required interior threshold luminance; the interior road luminance due to the daylighting without and with an anidolic system and the interior road luminance due to the necessary lamp scenarios required to produce the desired artificial lighting (which should exceed the required interior threshold luminance). Based on these calculations, the hourly electric lighting which could be saved due to an anidolic system was deduced for the chosen months. Yearly savings were calculated based on the hourly electricity savings and certain estimations. Two different methods were used: one depending on the frequency distribution of the exterior luminance of the tunnel surroundings "seen" by an oncoming driver, and the other, on the summation of the possible daily savings and on the monthly sunshine probability. The two extreme tunnel surroundings were such that from a safe stopping distance; in the first case which had high mountains, a driver could "see" no sky and in the second case, where there were no mountains, about 25 % of a driver's view consisted of sky.

The first studied tunnel with an anidolic system, which is certainly not the optimal solution for saving electricity, indicates that the savings due to an anidolic system at the south facing portal are relatively small (about 500 kWh/a), which corresponds to about 15% of the electricity required in the first section of the tunnel entrance. These savings are in addition to those possible due to daylight alone. The savings for a tunnel without mountains were higher (about 840 kWh/a) corresponding to about 23% savings in the first tunnel section. Higher savings are possible if the catching area of the anidolic system is increased. Rough estimations for the total Swiss tunnel situation give possible yearly savings of about SFr. 24'000.- if one assumes the current rate for electricity. Further investigations show that introducing an anidolic system at the tunnel mouth is economically more viable than using photo-voltaic cells for producing electricity. The anidolic system lies in a lower "electricity-cost" range than the photo-voltaic cells.

In addition, if the lamps are not reduced in power, an anidolic system can provide extra security for visual adaptation. Firstly, the overall luminance level is raised in the tunnel entrance and secondly, the ratio of the contribution towards the luminance due to daylight relative to that due to electric lighting is increased, which allows quicker adaptation of the eye for a given luminance level drop. The anidolic system can therefore decrease the eye adaptation time at tunnel entrances where regular traffic jams exist, and be useful in unlit tunnels in the mountains.

1. Introduction

The required road luminance in a tunnel is always a direct function of the area weighted luminance of the tunnel's immediate surroundings as seen by a driver approaching the tunnel mouth from a safe stopping distance. That is, the required luminance inside the tunnel entrance is in phase with the available daylight outside. Maximum required exterior (and interior) luminance levels are defined as design values. The exterior and interior road luminance obviously vary continuously with the weather and time of day and year. The daylight which enters a tunnel is mostly taken into account and the tunnel lamps reduced in power, based on the measured weighted surrounding luminance values.

2. Aim and purpose of the project

This study was aimed at establishing whether lighting energy could be saved at tunnel entrances by introducing new daylight systems to redirect the daylight deeper into the tunnel. Three main points favoured this investigation. First, the luminance requirements inside are in phase with the daylight availability. Secondly, a new daylight system – the anidolic system – with better efficiency than previous systems now exists. This system is not so easy to integrate in a normal building façade, but would be acceptable for tunnels. Thirdly, if no saving of lighting energy is possible, then the new luminance distribution in the tunnel entrance due to the anidolic system could be favourable. It could ameliorate the eye adaptation situation for drivers entering the tunnel by increasing the absolute luminance level deeper in the tunnel, rather than having a sudden drop in luminance very close to the entrance. In addition, an increase of the ratio of the luminance due to daylight to that due to the electric lighting can be positive.

Two different approaches can therefore be taken; either lighting energy savings are sufficiently high to warrant integrating such a system at the tunnel entrance; or they are insufficient and the quality of the lighting (without any lamp output reduction) which is due to higher luminance levels and to extra daylight deeper in the tunnel, can be considered.

The initial step was to verify the Radiance [7] computer models by comparing the calculated daylight factor results with those measured in a scale model under the artificial skies at the LESO laboratory, EPFL, Lausanne. Situations with and without an anidolic system were verified. Both the tunnel and anidolic system scale models were made at EMPA.

The study was based on Radiance simulations of the luminance of the tunnel surroundings, and of the tunnel entrance (threshold zone – fig. 1) due to daylight for a variety of sky conditions, seasons and tunnel situations for the cases without and with an anidolic system. The required threshold luminance was obtained from the surrounding luminance in the access zone, based on equations recommended by the CIE [1]. The tunnel entrance luminance due to the electric lighting was also simulated with Radiance. Using these simulation results, the possible yearly electric lighting savings due to the introduction of an anidolic system were calculated. Two different methods were used for this: one depending on the frequency distribution of the access zone luminance and the other on the summation of the possible daily savings weighted by the sunshine probability. The saving calculation was based either on the lamp or the threshold luminance. The economical situation for Switzerland was estimated using the energy savings based on the summation and threshold luminance method (realistic and conservative values) and on statistics for the Swiss road tunnels.

3. Basic theory of tunnel lighting

Luminance, rather than illuminance values, are critical for tunnel lighting as the visual aspect, seen by the driver, is important. The required tunnel road luminance as a function of depth is as follows (figure 1):

- L_{20} is the mean outside luminance of the tunnel entrance as seen by drivers from their safe stopping distance (SD) before the tunnel. The mean luminance is taken over a circular field of view subtending 20° at the driver's eyes and centred on the tunnel mouth. L_{20} is known as the luminance of the access zone.
  L_{20} is defined by:
  $L_{20} = \gamma * L_C + \rho * L_r + \varepsilon * L_e + \tau * L_{th}$, where L_C is the sky luminance, L_r the road luminance, L_e the surrounding luminance and γ, ρ ε and τ are the percentage of sky, road, surroundings and tunnel entrance respectively seen by the driver [1].
- L_{th} is the required interior road luminance of the threshold zone inside the tunnel.
  $L_{th} = k * L_{20}$ for a distance equal to half the stopping distance, where "k" depends on the type of lighting system (symmetric or counter beam – see below), vehicle speed (v) and type of tunnel (density of traffic etc.).
- The interior road luminance then decreases linearly to L_{fe} where $L_{fe} = 0.4 * L_{th}$ (at C), for a distance equal to half the stopping distance.
- The interior luminance is then given by $L_{tr} = L_{fe}\ (1.9+d/v)^{-1.4}$ where v is the vehicle speed and d the distance travelled after the first section which is equal to the stopping distance (point C in figure 1).
- Two main types of artificial lighting are available: counter-beam lighting where the light beam points towards the driver and symmetrical lighting where the beam is symmetrical with respect to the lamp.

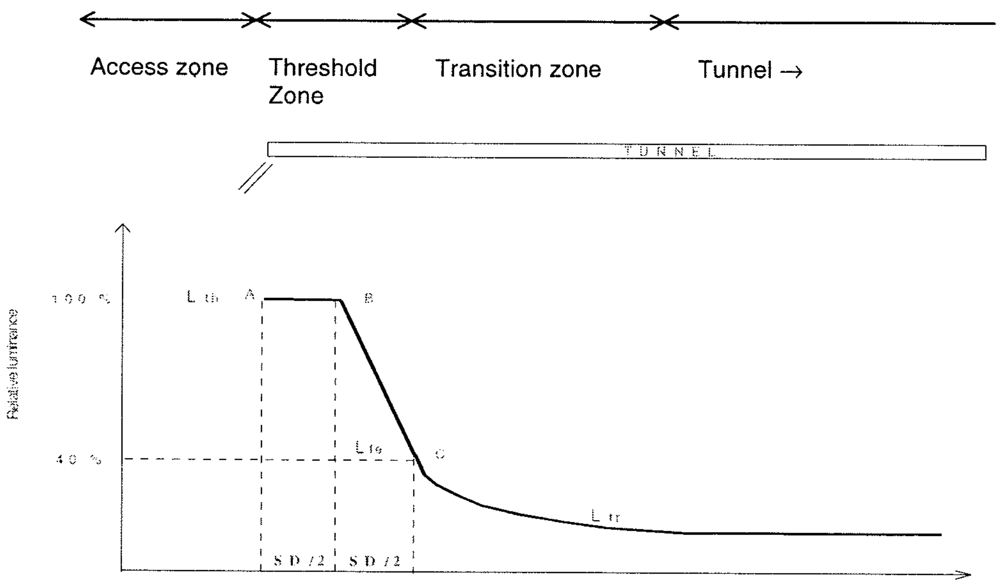
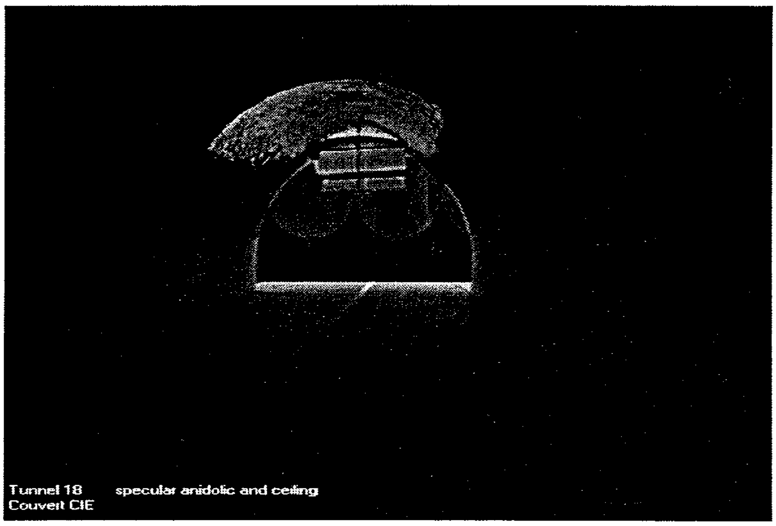


Figure 1: Relative luminance of the road in the tunnel. SD = stopping distance.

4. Comparison of measurements and calculations of daylight factors in a tunnel



Photograph of the scale model tunnel with a specular anidolic system and white ceiling

In order to check the simulations made with Radiance (UNIX version X,) [7], measurements on a scale model were made at the PB-LESO, EPFL (see appendix A). The scale models of an existing tunnel and an anidolic system were built at the EMPA. The measurements and the simulations made with Radiance, for both overcast and clear sky conditions (either without or with sun), were very close if no anidolic system was present. If an anidolic system was integrated, the comparison results between the daylight factors were good (2% to 6% deviation) for an overcast sky and acceptable (3% to 21% deviation) for a clear sky without sun. The problems encountered for a clear sky with sun are accountable and discussed in appendix A. A detailed description of the comparison is given in appendix A.

5. Description of method

5.1 Choice of tunnel

Each tunnel location, orientation, type of sky and time of year and day will produce both different required threshold tunnel luminance levels (L_{th}) and different interior luminance levels due to daylight. To save electric lighting with a daylighting system, one requires: high interior "daylight" luminance levels and mainly a high increase of "daylight" luminance (Δ_{lum}) due to the daylight system – an anidolic system in this study - hence high solar radiation is necessary. The tunnels were therefore situated in Wallis. A south facing portal allows a maximum of daylight and sun to enter the tunnel entrance (figure 2). Δ_{lum} must also be sufficiently high to allow switching off or down of a lamp, Finally, if the required threshold luminance is high, then the lamp power is also high and switching down or off produces higher absolute energy savings. So the dynamic interactions are complex, especially with stepping down of lamp output.

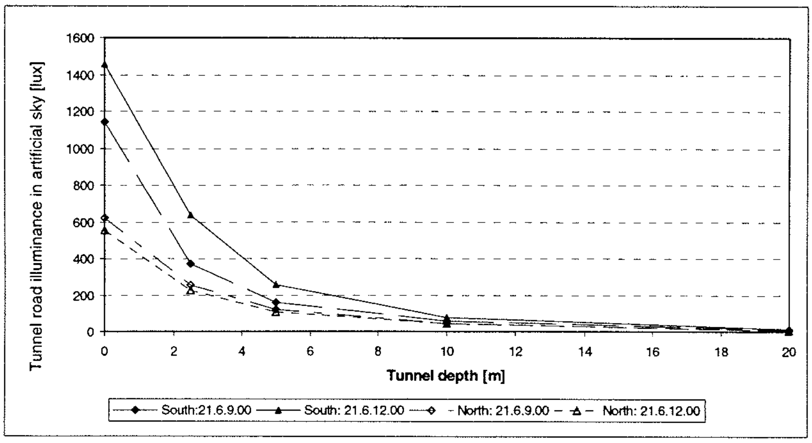


Figure 2: Comparison of tunnel road illuminance at the north and south portals of a tunnel

Two tunnels, both with portals facing south and with normal roads, were selected. The first had low access zone luminance values (L_{20}) as the tunnel entrance was surrounded by mountains above and on the sides so that no sky was "seen" by drivers in their field of vision defined by a 20° cone, hence a low required threshold luminance (L_{th}) existed.
The second tunnel had no mountains above it so that drivers could "see" sky in their field of vision defined by a 20° cone, producing higher access zone luminance values (L_{20}) and higher required interior threshold luminance levels (L_{th}). The amount of sky in the driver's 20° field of view was 24% of the whole view. The higher L_{th} implies more powerful lamps with higher wattage to provide the required luminance. The interior "daylight" luminance will also increase for the second case, as daylight from the northern section of the sky will be reflected either by the anidolic scoop or by the road into the tunnel as no mountains block the skylight (see appendix B, point 4)).

The factor "k" in $L_{th} = k * L_{20}$ was kept constant in both cases, corresponding to medium density of non uniform traffic, curves in the vicinity of the tunnel and symmetrical tunnel artificial lighting. Symmetrical lighting, rather than counter-beam was chosen because daylight is in fact pro-beam in the tunnel entrance and therefore symmetrical lighting is a better match [1].

5.2 Daylighting systems

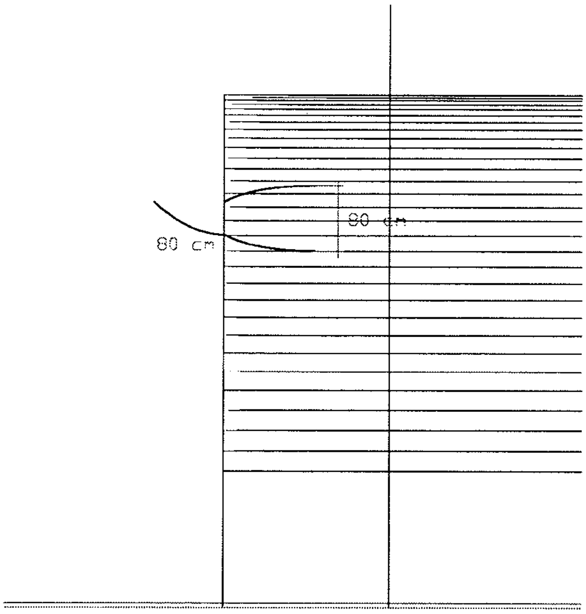


Figure 3: Anidolic system in tunnel

A zenithal anidolic system (figure 3) was chosen as it gives the best results for increasing the illuminance levels deep in a room [4]. It consists of an outside scoop which concentrates the zenithal rays and inside reflectors which direct the rays towards the tunnel depth. The exterior horizontal scoop depth and interior height of the system were both 80 cm and its width 6m (see appendix B). It was made of aluminium with a reflection coefficient of 0.9 and was combined with a white specular tunnel ceiling ($\rho_{ceiling}$ = 0.827). In addition, a light pipe (ρ = 0.9), which was 30 m long, and connected to the anidolic system, with opening slits every 4m after the first 10m, was also simulated. The anidolic system should be efficient for both sunny and overcast conditions as 50% of the time is overcast in Switzerland.

A system with vertical slits in the tunnel entrance walls was originally considered as an possible alternative, but the literature research indicated that such a system had two major drawbacks: firstly, it caused flickering of the light levels which was very uncomfortable for drivers and secondly, irregular icing up of the road occurred. It was therefore rejected.

5.3 Determination of $L_{20,max}$ and $L_{th,max}$

The luminance L_{20} in the access zone is defined as the mean luminance of the tunnel entrance surroundings as seen by drivers from a safe stopping distance (SD)* before the tunnel. $L_{20,max}$, the maximum design value of L_{20}, can be determined using either the CIE equation (1) and recommended maximum values for the various luminance levels of the surroundings [1]; or the CIE equation and calculated maximum luminance levels of the tunnel surroundings in question or finally, from the calculations of the cumulative frequency distribution (e.g. for a given percentage – 95 % - of the frequency distribution, L_{20} does not exceed $L_{20,max}$) (figure 6) [2].

$$L_{20,max} = (\gamma * L_{sky} + \rho * L_{road} + \varepsilon_1 * L_{mountain} + \varepsilon_2 * L_{field}) / (1-\tau k) \qquad (1)$$

where γ, ρ, ε_1, ε_2 and τ are the percentages of sky, road, mountain, fields and tunnel mouth in the 20° cone field of view and L_{sky} is the luminance of the sky just above the tunnel, L_{road} is the luminance of the road in the access zone, $L_{mountain}$ is the luminance of the mountains and L_{field} is the luminance of the fields. (In some cases τ k is small and can be neglected [1])

<u>For the first tunnel</u>, no sky is "seen" by the driver so that:

$$L_{20,max} = (0.28 * L_{road} + 0.53 * L_{mountain} + 0.02 * L_{field}) / (1- 0.17 * k) \qquad (1a)$$

as $\gamma = 0$, $\rho = 0.28$, $\varepsilon_1 = 0.53$, $\varepsilon_2 = 0.02$ for the first tunnel considered.

* $SD = (V_{max}/10)^2 + 3 * (V_{max}/10)$

L_{th} is the threshold road luminance in the first section in the tunnel whose length corresponds to half the stopping distance and the value of k (in equation 2) is given by CIE tables [3].

$$L_{th,max} = k * L_{20,max} \qquad (2)$$

$L_{th,max}$ defines the required artificial lighting luminance in the tunnel. The $L_{20,max}$ and $L_{th,max}$ (with k = 0.05) values for the first tunnel are given in table 1. The first method, based on very approximate recommended luminance values at the south portal of a tunnel ([3], appendix A, table 4) gives **2491** cd/m^2. In the second method, the maximum luminance values (for sun and overcast conditions) for the tunnel surroundings, which were calculated by Radiance, were used in equation 1. One then obtains $L_{20,max}$ = **1551** cd/m^2. (These values exclude the snowy mountain luminance for sunny conditions in January, as it is an exception and not necessarily to be completely covered by the artificial lighting. $L_{20,}$ for overcast conditions in January are below the $L_{20,max}$ value of 1546 cd/m^{2,} hence there is sufficient lighting for these conditions.) The third method uses luminance values of the surroundings based on the fundamental theory describing sky luminance, and gives $L_{20,max}$ = **1300** cd/m^2 [2]. This value (table 1) is the maximum access luminance for a cumulative frequency of 95%, hence snow covered mountains in sunny conditions are also excluded. (40% sunshine probability for January corresponds to 3.4 % of the annual time.)
The last two very different approaches for calculating $L_{20,max}$ (Radiance and cumulative frequency) provide similar results. The first method is more conservative and general.

Table 1: Comparison of the safe maximum values of $L_{20,max}$ and $L_{th,max}$ for a south portal evaluated by different methods for 0% sky in drivers' view.

Method	**Max. sky luminance [cd/m^2]**	**Max. road luminance [cd/m^2]**	**Max. mountain luminance [cd/m^2]**	**Max. field luminance [cd/m^2]**	**0% sky in field of view [cd/m^2]**	**0% sky in field of view [cd/m^2]**
					$L_{20,max}$	**$L_{th,max}$**
$L_{20,max}$CIE_recommended values	6000	3000	3000	2000	2491	125
$L_{20,max}$ CIE_Radiance (sun) (overcast)	2055(mar.) 3615	4722(june) 886	380 *)(mar) 40	710 (june) 122	1551 ——	78
$L_{20,max\,95\%}$ based on the cumulative frequency			1000		1300	65

*) The luminance of the mountains (calculated with Radiance) is much lower than the values given in the CIE tables. This is due to the low reflection value (0.018 corresponding to dark fir trees - based on an existing tunnel) used for the mountains in the Radiance model, leading to a luminance of about 370 cd/m^2 compared to 1000 cd/m^2 in the cumulative frequency method [2] and 3000 cd/m^2 as general recommendation in the CIE method [1] .

For the second tunnel, only the first two methods were used to calculate $L_{20,max}$ and $L_{th,max}$ (with k = 0.05), where:

$\gamma = 0.24$, $\rho = 0.28$, $\varepsilon_1 = 0.29$, $\varepsilon_2 = 0.02$ for equation 1. This gives

$$L_{20,max} = (0.24 * L_{sky} + 0.28 * L_{road} + 0.29 * L_{mountain} + 0.02 * L_{field}) / (1-\tau k) \qquad (1b)$$

The results are given in table 2, where the first method gives $L_{20,max}$ = **3217** cd/m^2 and the second method gives $L_{20,max}$ = **2339** cd/m^2. One sees that for both methods $L_{20,max}$ is higher for the second tunnel with sky in the driver's field of view than for the first tunnel with high mountains and no sky visible. $L_{th,max}$ determines the lamp design luminance. As $L_{20,max}$ is higher for the second tunnel, it mean that lamps with higher wattage are required there.

Table 2: Comparison of the safe maximum values of $L_{20,max}$ and $L_{th,max}$ for a south portal evaluated by different methods for 24% sky in drivers' view.

Method	**Max. sky luminance [cd/m²]**	**Max. road luminance [cd/m²]**	**Max. mountain luminance [cd/m²]**	**Max. field luminance [cd/m²]**	**24% sky in field of view [cd/m²]**	**24% sky in field of view [cd/m²]**
					$L_{20,max}$	$L_{th,max}$
$L_{20,max}$CIE_recommended values	6000	3000	3000	2000	3217	161
$L_{20,max}$ CIE_Radiance (sun)	2070(June)	4746(june)	375 ⁾(mar)	714(June)	2339	117
(overcast)	3615	962	39	136	——	

5.4 Determination of the hourly required interior threshold road luminance: L_{th}

In reality a luminance meter outside the tunnel measures the luminance L_{20} seen by the driver and regulates the luminance inside the tunnel by reducing or increasing the lamp output (stepped or dimmed). Both L_{20} and L_{th} vary continuously during the year.

In the study, the luminance values of the sky just above the tunnel, road, mountains and field "seen" by the driver as he or she approaches the tunnel entrance are calculated with Radiance for all the considered hours and months. Equations (3) and (4) are used to calculate the access zone luminance L_{20} and the corresponding required interior threshold luminance, L_{th}, for each hour of the 21st each considered month.

$$L_{20} = (\gamma * L_{sky} + \rho * L_{road} + \varepsilon_1 * L_{mountain} + \varepsilon_2 * L_{field}) / (1-\tau k) \qquad (3)$$

$$L_{th} = k * L_{20} \qquad (4)$$

The percentages of sky, road, mountain, fields and tunnel mouth in the 20° cone field of view, (γ, ρ ε_1 ε_2 τ) vary, as given above for the two tunnels considered.

In the first case, with high mountains surrounding the tunnel entrance and no sky visible (γ = 0) by the driver, the road is a normal mountain road with bi-directional traffic, so that a speed between 60 and 84 km/h can be assumed which means a stopping distance of 54 – 96m. The Radiance calculations were made with a stopping distance of 54m, which means that the L_{20} value for a given hour and day, was derived from luminance values "seen" by the driver from a distance of 54m from the tunnel entrance. For the boundary conditions described above and symmetrical lighting "k" is about 0.04 according to the SEV recommendations and 0.05 according to the CIE. For conservative reasons k = 0.05 was used.

In the second case, the driver " sees" a section of the sky above the tunnel entrance (γ = 0.24) which replaces the mountains in the previous case. The sky is much brighter than the mountains, hence L_{20} will be higher and, assuming that the other boundary conditions are the same, then the required interior luminance and the lamp powers will be higher.

5.5 Luminance and energy calculations for tunnel entrances

Various auxiliary situations were simulated with Radiance to understand the behaviour of the daylighting in the threshold zone of a tunnel before starting the main simulations. These are described briefly in appendix B and cover the following points:

1. luminance as a function of road width and ist consequence on the simulation method
2. anidolic system dimensions (high and shallow anidolic systems with high mountains)
3. dark and white ceiling for the tunnel entrance
4. high and low mountains (or hills) without and with an anidolic system
5. reflection coefficient of the mountains
6. view direction in the tunnel
7. variation of interior luminance for different months

Based on the above study, the following strategy was adopted:

A shallow (smaller collecting area) specular anidolic system combined with specular white ceiling, in order to obtain a maximum reflection from the system and ceiling, was chosen. It was positioned above the space reserved for vehicles. Extrapolations for a larger scoop can be made. Dark high mountains were assumed in the first set of simulations and no mountains in the second. Simulations were made starting the calculations at a distance of 110m inside the tunnel in the dark region to obtain maximum accuracy.

The calculations are split into three parts: Radiance calculations of the interior tunnel luminance due to daylight with or without anidolic system, Radiance calculations of the luminance of the tunnel surroundings and the required threshold luminance which should be provided by the electric lighting and finally possible savings of electricity due to the anidolic system. The first two steps are accurate simulations whereas the third involves assumptions and interpolations.

5.5.1 Radiance simulations

The plan for the Radiance luminance simulations of the tunnel road and exterior surroundings, for the daylit hours of the 21st of each chosen month, is given in table 3. The simulations were made for a clear sky with sun for 5 selected months, as well as for overcast conditions for June and January, without and with an anidolic system. One therefore obtains the hourly tunnel road luminance values as a function of tunnel depth.

Table 3: Overview of Radiance hourly simulations as a function of tunnel depth for the calculation of the yearly electric savings with an anidolic system for each tunnel situation.

Sky percentage in driver's view		**6.2.1 Clear sky with sun**					**Overcast sky [a]**	
		Jan (snow)	March	May	June	December	June	Jan (snow)*
0% sky	Without anidolic	√	√	√	√	√	√	√
	With anidolic	√	√	√	√	√	√	√
24% sky	Without anidolic	√	√	√	√	√	√	√
	With anidolic	√	√	√	√	√	√	√

(a) The results for the eight solar altitudes for June were used to interpolate the results for overcast conditions for all the other months except January where the mountain luminance was different due to the snow.

5.5.2 Determination of the lamp scenarios required for the artificial lighting

High pressure sodium lamps, at 2m intervals, are normally used in tunnels, as the response time is much shorter than for low pressure lamps. The required night time average lighting is about 1 cd/m^2, which means that the spacing between illuminated lamps can increase and only few lamps need be switched on then. The luminance increments between sequential lighting scenarios during the day should not exceed 10-25 cd/m^2. (For lamps with high wattage, the luminance increment does sometimes exceed these values for high lamp luminance values.) In the situation with high mountains, 250W lamps are required to cover the maximum threshold luminance ($L_{th,max}$) (figure 4) although their maximum power (111cd/m^2) is only used to a very limited extent in the case of snow covered mountains. 150W lamps do not provide the maximum threshold luminance value. In the situation with low mountains (24% sky in field of view), the 250W lamps do not cover the $L_{th,max}$. value calculated with Radiance results, whereas the 400W lamps allow some margin.

It was assumed that the lamps could function at four levels (full on, ¾, ½ and ¼ luminous flux (where the respective partial power demand was higher than the corresponding percentage of the power). Possible lamp scenarios are give in table 4, with the required fraction of the maximum. The first lamp is situated at a depth of 8m due to the available daylighting. Each of these scenarios were simulated with Radiance to obtain the corresponding interior road luminance (figure 4).

A lamp scenario, which provides a sufficiently high luminance to exceed the calculated hourly required threshold luminance, L_{th}, for each case has to be selected (figure 5) The hourly savings due to daylight and the anidolic scoop can then be evaluated as a function of tunnel depth (table 5).

Table 4: Possible lamp scenarios (e.g. T3: first lamp is ½ on, the second on and third off).

Distance in tunnel [m]	T6	T5	T4	T3	U32	T2	U21	T1	U1
8	1	0.5	1	0.5	0.5	1	0.75	0.5	0.25
10	1	1	1	1	0.5	0	0	0	0
12	1	1	0	0	0.25	0	0	0	0
14	1	0.5	1	0.5	0.5	1	0.75	0.5	0.25
16	1	1	1	1	0.5	0	0	0	0
18	1	1	0	0	0.25	0	0	0	0
20	1	0.5	1	0.5	0.5	1	0.75	0.5	0.25
22	1	1	1	1	0.5	0	0	0	0
24	1	1	0	0	0.25	0	0	0	0
26	1	0.5	1	0.5	0.5	1	0.75	0.5	0.25
28	1	1	1	1	0.5	0	0	0	0
30	1	1	0	0	0.25	0	0	0	0

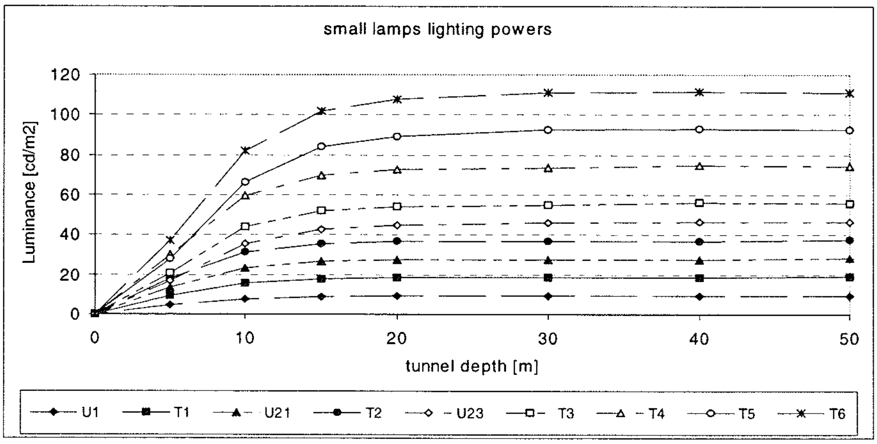


Figure 4: Tunnel road luminance provided by the various lamp scenarios given in table 4.

5.5.3 *Calculations of the tunnel luminance due to daylight, and possible energy savings*

Radiance simulations

The calculations, made with Radiance, of the hourly tunnel road luminance levels with and without an anidolic system (combined with a white ceiling) can be compared with the luminance available with the chosen lamp scenario (table 4) and with the hourly required threshold luminance level L_{th} in order to determine the useful increase in luminance due to the anidolic system (figure 5). Two luminance levels are available as comparisons to determine when lamps can be switched off or down to save energy: the lamp luminance or the threshold luminance. This is done every two meters, starting at 8m depth.

Hourly and daily savings for a particular month

Figure 5 shows typical results of these four luminance levels as a function of tunnel depth.

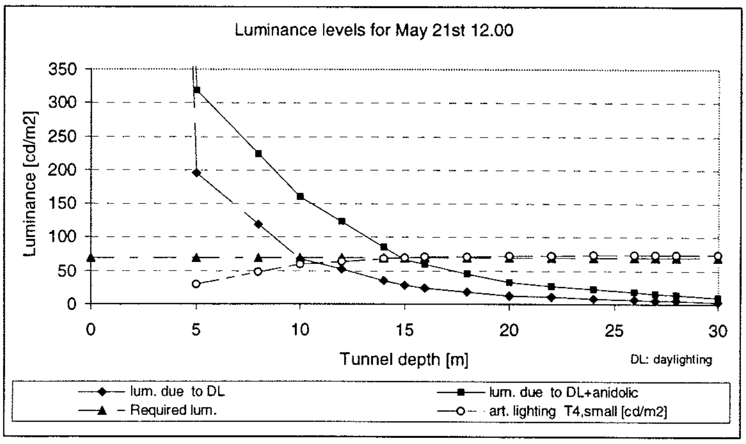


Figure 5: Tunnel with mountains: Different tunnel luminance levels due to daylight alone, daylight with an anidolic system, the lamps and the threshold luminance L_{th} for May 21st 12.00.

Using these results one can then decide when and by how much a lamp can be switched off (either fully or partially) at a given distance in the tunnel due to the "free" daylight and due to the anidolic system with a white ceiling. (For example, at a given depth, it could be switched down to ½ light output due to daylighting and to ¼ due to daylighting plus an anidolic system. This would lead to a saving of power, due to the anidolic system alone, corresponding to switching down from ½ power to ¼ power, (in our first case from 150W to 95W, saving 55W.) The possible savings for each lamp (every 2m) can be summed for the relevant tunnel depth (max. 30m) for each hour. In this way, the hourly saved electricity corresponds to a calculated access zone luminance L_{20}. The hourly savings can then be summed to give the daily savings.

Yearly energy savings

Two very different approaches were used to calculate the possible yearly savings due to an anidolic system. To save lighting energy the lamps can either be controlled by step control (switched either partially or totally off) or dimmed continuously.

<u>Method 1: Yearly savings based on the L_{20} frequency distribution calculation method:</u>

For each range of L_{20} obtained (e.g.300-400 cd/m^2) the frequency of L_{20} occurrence, calculated for the tunnel in question, was recorded from the cumulative frequency curve (figure 6) [2]. The average savings for that L_{20} range were obtained from the Radiance calculations. The weighted savings (based on the frequency value) per range of L_{20} were obtained to give the possible yearly electricity savings (table 6). This was done for both an anidolic system with white ceiling alone, for "free" daylight plus an anidolic system (plus white ceiling), both with stepped artificial lighting, and for anidolic system with white ceiling alone with dimming of the artificial lighting, although this is not economical due to its initial cost (table 9).

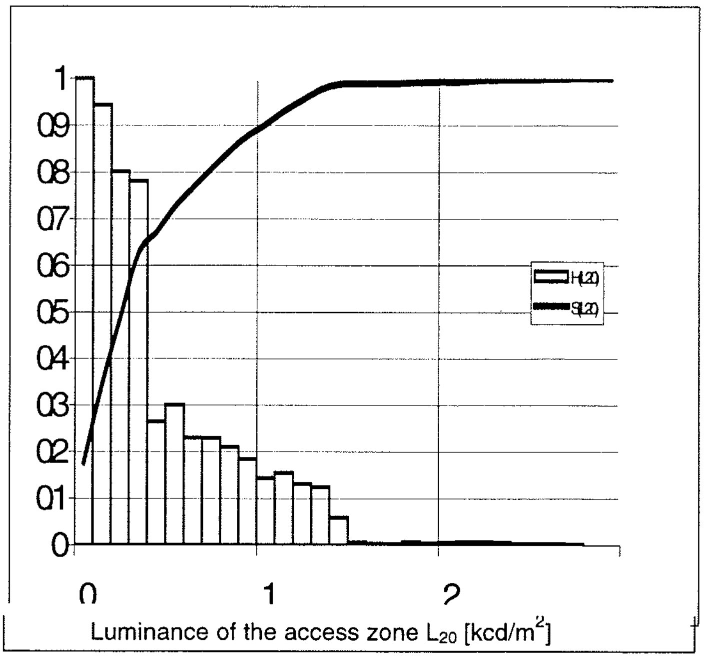


Figure 6: Frequency and cumulative distribution of the luminance of the access zone L_{20} for the south portal of a tunnel in Wallis, with a road surface R3_0.08.

Method 2: Yearly savings based on the summation method:

This second approach is based on the daily electricity savings for the 21st of five selected months (table 3). Each chosen month is representative of other months for the yearly saving calculations (except June and January - with snow - which are unique). The hourly savings for a given month, with a clear sky and sun, are weighted by the monthly sunshine probability for that month and then added to the hourly savings for overcast conditions (based on the corresponding relevant solar altitudes for the month in question) and likewise weighted by 1 minus the sunshine probability. These hourly savings are summed for the 21st of each relevant month and used to obtain the yearly savings (tables 5, 7 and 8). The savings can be calculated with respect to the luminance provided by the artificial lights or the required threshold luminance. Near the tunnel entrance, the former luminance will be lower than the latter; but where the daylight contribution is much lower, the artificial light luminance is higher than the threshold luminance (figure 5). Hence the two methods provide different savings. The method using the threshold luminance as base is more realistic and is independent of the exact lamp luminance. It gives lower savings (see section 8.1), and is therefore used for the second tunnel without mountains, the economical analysis and the final discussion.

6. Results

6.1 Luminance levels in both the tunnels considered - with no sky visible and with sky visible by the oncoming driver

6.1.1. Radiance simulations

The two figures 7 and 8, corresponding to tunnels with and without mountains respectively, show the interior road luminance with an anidolic system plus white ceiling and without an anidolic system with a normal (dark) ceiling for sunny conditions. These results are plotted for 12.00 on December 21st and May 21st. with the corresponding value of $L_{th.}$ They show the different interrelated behaviours which occur. For December, L_{th} is low because the road and surrounding luminance levels are low as the sky is not bright. Due to the low solar altitude which allows sunlight to penetrate deep into the tunnel, there is sufficient daylight inside the tunnel to satisfy the required L_{th} (31,5 cd/m²) up to a distance of 20m. Savings with the anidolic scoop only start at 20m depth. (The anidolic scoop must just cut off the sunrays at a depth of 15m inside the tunnel causing the sudden drop in luminance.) For a tunnel in May without mountains (case with 24% sky), the situation is different: L_{th} is high (92 cd/m²) due to a bright sky which is now "seen" by the driver; the daylight luminance just inside is much lower than for December as the sun is higher and its rays do not penetrate deep into the tunnel. Hence, there is already insufficient daylight to provide the required L_{th} at 9m depth and saving of electric lighting can be achieved with the anidolic scoop. The interior road luminance with an anidolic scoop is higher if there are no mountains than if high mountains exist. This is due to

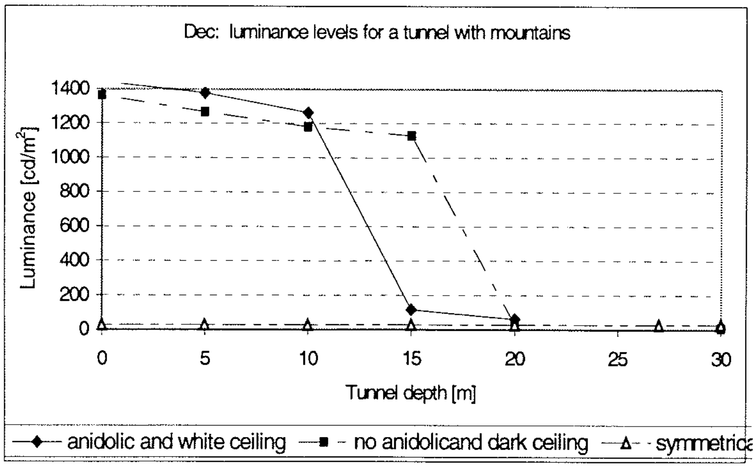


Figure 7: Tunnel with mountains: Luminance with and without anidolic system and luminance from the artificial lights for sunny conditions on December 21st 12.00.

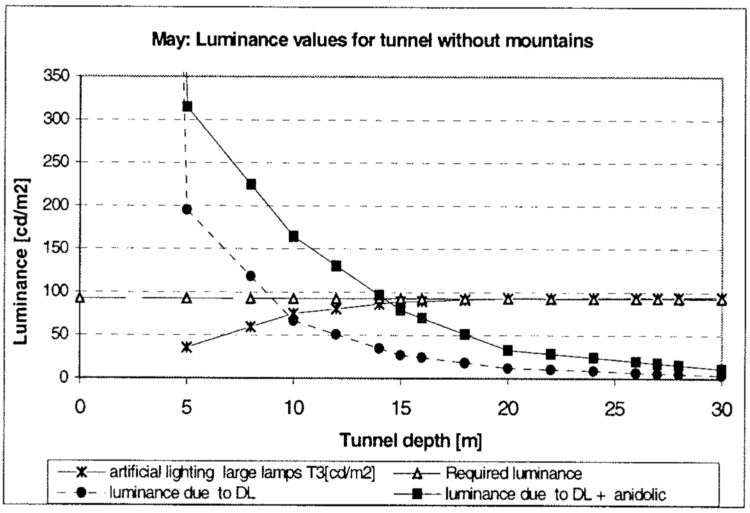
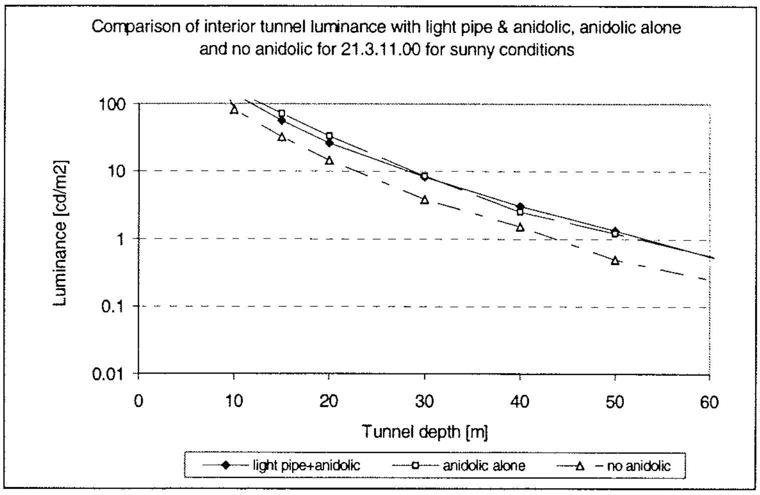


Figure 8: Tunnel without mountains: Luminance with and without anidolic system, luminance from the artificial lights as well as the threshold luminance for sunny conditions for May 21st 12.00. DL: daylight.

some rays from the northern part of the sky being reflected spectrally and a fraction being reflected diffusely into the tunnel by the anidolic scoop. In addition rays from the northern part of the sky can be reflected diffusely by the outside road into the tunnel.
At the tunnel mouth, the luminance with an anidolic scoop is higher than without, as a white ceiling is combined with the anidolic system.
The presence of the anidolic system can also affect the mountain luminance slightly just above the tunnel. The sky and zenithal luminance values obviously remain unchanged.



A 30m light pipe with slits every 4m after the first 10m does increase the luminance very slightly after 30m, but the increase is very small compared to that possible with an anidolic system and white ceiling (figure 9). Between 10m and 30m the interior luminance with light pipe is lower than without, so that possible savings are just shifted.

Figure 9: Luminance with no system, with an anidolic system, and an anidolic system with a light pipe for a tunnel surrounded by high mountains.

6.2 Tunnel with no sky visible by the drivers from a safe stopping distance from the tunnel entrance

6.2.1 Hourly and daily energy savings

Table 5: Daily savings, for clear sky conditions with sun, due to an anidolic system alone and an anidolic system plus "free" daylight for May 21st. The calculations are based on the required threshold luminance L_{th}. (DL: daylight).

Hour	Step: saved electricity with anidolic	Step: saved electricity with anidolic	Step: saved electricity with DL & anidolic	Dimmed: saved electricity with anidolic	L_{20}	Type of lamp scenario
[h]	[W]	[%]	[W]	[W]	[cd/m^2]	
9.00	345	21.6	750	313	941	T3 - 0.5;1;0
10.00	400	20	1155	336	1164	T4 - 1;1;0
11.00	550	27.5	1105	427	1316	T4 - 1;1;0
12.00	500	25	1055	450	1390	T4 - 1;1;0
13.00	550	27.5	1055	456	1379	T4 - 1;1;0
14.00	500	25	1105	410	1287	T4 - 1;1;0
15.00	450	22.5	1205	376	1118	T4 - 1;1;0
16.00	245	15.5	600	287	879	U23 - 0.5;0.5;0.25
average		**23.08**			**1184.25**	
total [kWh]	**3.54**		**8.03**	**3.05**		

Based on the hourly luminance levels with and without anidolic system with white ceiling, the threshold luminance and the lamp luminance, the possible new lamp scenarios (fully on, ½ on, off etc.) due to switching lights down or off can be obtained for daylight combined with the anidolic scoop and for daylight alone. Two lamp control strategies (stepped and dimming) are considered. This results in the lighting energy savings due to an anidolic system. These results are a function of tunnel depth and available for every daylit hour of the 21st of the 5 chosen months (table 5).

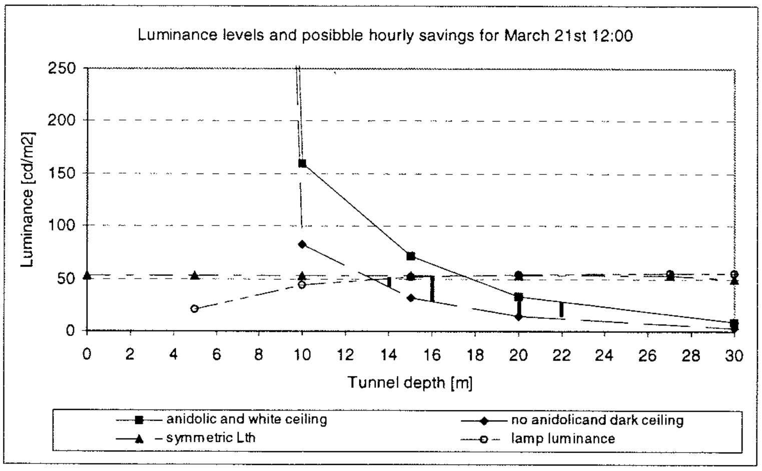


Figure 10: Luminance levels with no anidolic, with an anidolic system, the threshold luminance L_{th} and the luminance due to the lamps for March 21st at 12.00.

Three examples of various luminance levels for May 21st, December 21st and March 21st are shown in figures 5, 7 and 10 respectively for a tunnel with surrounding mountains. In addition, figure 10 shows the useable differences in luminance levels ($\Delta_{lum,elec}$) due to the anidolic system (|). Depending on the magnitudes of $\Delta_{lum,elec}$, the lamps can be turned fully or partially off at various tunnel depths.

6.2.2 Yearly energy savings

Method 1: Yearly savings based on the L_{20} frequency distribution calculation method.

Table 6: Average hourly savings and the corresponding frequency, for each range of L_{20}, due to an anidolic system with stepped control of the tunnel lamps.

L_{20} range [cd/m²]	Average savings / hour [W]	Frequency (from distribution)	Weighted savings [W]
0 –100	0	1	0
100 –200	56.1	0.95	53.3
200 – 300	115	0.8	92.2
300 – 400	245	0.78	191.1
400 – 500	115	0.27	31.0
500 – 600	183	0.3	54.9
600 – 700	273	0.23	62.7
700 – 800	300	0.23	69.0
800 – 900	286	0.21	60.1
900 – 1000	288	0.185	53.2
1000 – 1100	390	0.145	56.6
1100 – 1200	500	0.16	80.0
1200 – 1300	438	0.125	54.7
1300 – 1400	488	0.12	58.6
1400 – 1500	598	0.06	35.9
		5.565	953.33

Table 6 shows the average calculated savings (using the artificial lighting luminance as base) for each particular L_{20} range as well as the possible "yearly" savings based on the frequency distribution versus L_{20} given in figure 6. The "yearly" savings in table 6 exclude sunny January results with $L_{20} > 1500$.

Average number of useful daylight hours/day = 8.52
Savings for January with snow and sun = 9.51 kWh
Number of days excluding sunny days in January = 352.5
Total savings = ((953.33 / 5.565) * 352.5 * 8.52) / 1000 + 9.51 = **524 kWh**

Similar calculations can be made for the case with the free daylight and the anidolic system taken together with stepped control of the lamps and the anidolic alone with continuous dimming of the lamps (table 9).

Method 2: Yearly savings based on the summation of daily electricity savings for the 21st of five chosen months based either on the threshold luminance or on the artificial lighting luminance respectively.

Daily results for a clear sky with sun (as shown in table 5) and for an overcast sky are used to obtain the possible monthly and yearly savings, taking the sunshine probability into account and the threshold luminance as base (table 7). Similar results are available if the calculations are based on the artificial lighting luminance. (table 7b). Table 8 indicates the same results but extended to include the electricity used if there is no switching off of the lamps for the same L_{20}. The calculations are based on the required threshold luminance, and indicate the possible percentage savings.

Table 7 Monthly and yearly electric energy savings for tunnel lighting, for a tunnel with high mountains above it, with an anidolic system at the entrance and stepped control of the lamps. The calculations are based on the threshold luminance values.

month	sun: savings [kWh]	overcast: savings [kWh]	total energy savings per month [kWh]	based on daily energy of	sunshine probability
jan_snow	0.63	8.51	9.14	jan_snow	40.35
feb	33.43	0.00	33.43	march	48.14
march	40.89	0.00	40.89	march	53.19
april	40.25	0.00	40.25	march	54.1
may	56.71	4.94	61.65	may	51.68
june	67.81	4.64	72.45	june	54.6
july	67.90	3.90	71.80	may	61.87
aug	45.38	0.00	45.38	march	59.03
sep	43.30	0.00	43.30	march	58.2
oct	43.50	0.00	43.50	march	56.58
nov	16.64	0.00	16.64	dec.	43.67
dec	15.81	0.00	15.81	dec.	40.16
total [kWh/a]	**472.25**	**21.99**	**494.24**		**51.80**

Table 7b: Monthly and yearly electric energy savings for tunnel lighting, for a tunnel with high mountains above it, with an anidolic system at the entrance and stepped control of the lamps. The calculations are based on artificial light luminance values.

month	sun: savings [kWh]	overcast: savings [kWh]	total savings per months [kWh]	based on daily energy of:	sunshine probability
Jan_snow	9.51	3.70	13.21	Jan_snow	40.35
Feb.	41.11	7.12	48.23	March	48.14
March	50.29	7.11	57.40	March	53.19
April	49.50	6.75	56.25	March	54.1
May	50.31	17.47	67.84	May	51.68
June	69.12	16.47	85.59	June	54.6
July	60.22	13.83	74.05	May	61.87
Aug.	55.81	6.22	62.03	March	59.03
Sep.	53.25	6.14	59.39	March	58.2
Oct.	53.50	6.60	60.10	March	56.58
Nov.	18.08	4.22	22.30	Dec.	43.67
Dec.	17.18	4.64	21.82	Dec.	40.16
Total [kWh/a]	**527.88**	**100.33**	**628.21**		**Av.: 51.80**

Table 9 supplies an overview of the various results with different methods. Methods 1 and 2 are based on artificial lighting luminance and methods 3 and 4 on the required threshold luminance.

Table 9: South portal of a tunnel surrounded by mountains: Yearly savings for the anidolic system with stepped lamp control or dimming of lamps and yearly savings for an anidolic system with "free" daylight with stepped control of the lamps.

Method	**Yearly savings [kWh/a]**		
	Anidolic_step	**Anidolic + daylight_step**	**Anidolic_dimmed**
1. L20 distribution [kWh/a]*	**524**	**1488**	**437**
2. Sum of monthly values [kWh/a]_1*	**628**	**1643**	**581**
3. Sum of monthly values [kWh/a]_2**	**494**	**1789**	**496**
4. L20 distribution [kWh/a]**	**371**	**-**	**-**
Average 1 – 3 [kWh/a]	549	1640	505
Average 1 – 4 [kWh/a]	504	-	-
Difference between 1 and 2 [kWh/a]	104	155	144
% savings for average of 1 – 3 [%]	17	50	15
% savings for method 3 [%]	**15**	**54**	**15**

One sees that the frequency distribution method 1 gives lower savings than the summation method 2 with the lamp luminance used as base. Lower savings are obtained if the calculations are made with respect to the threshold luminance (methods 3 and 4); the frequency method giving the lower savings.

The savings obtained with the summation method based on the threshold luminance

Table 8: Anidolic system alone: yearly electric savings and total energy requirements in the first 30m.

month	sun: total electrical lighting energy [kWh]	sun: savings [kWh]	sun: percent savings [%]	overcast: total electrical lighting energy [kWh]	overcast: savings [kWh]	overcast: percent savings [%]	sun + overcast total electrical lighting energy [kWh]	sun + overcast total savings [kWh]	based on daily energy of:	sunshine probability
Jan_snow	300.20	0.63	0.21	64.35	8.51	13.22	364.55	9.14	Jan_snow	40.35
Feb	166.60	33.43	20.07	56.92	0.00	0.00	223.52	33.43	March	48.14
March	203.80	40.89	20.06	56.88	0.00	0.00	260.69	40.89	March	53.19
April	200.60	40.25	20.06	53.98	0.00	0.00	254.58	40.25	March	54.1
May	243.20	56.71	23.32	106.05	4.94	4.66	349.25	61.65	May	51.68
June	300.74	67.81	22.55	96.43	4.64	4.81	397.17	72.45	June	54.6
July	291.15	67.90	23.32	83.69	3.90	4.66	374.84	71.80	May	61.87
Aug	226.18	45.38	20.06	49.79	0.00	0.00	275.97	45.38	March	59.03
Sep	215.81	43.30	20.06	49.16	0.00	0.00	264.96	43.30	March	58.2
Oct	216.79	43.50	20.07	52.76	0.00	0.00	269.56	43.50	March	56.58
Nov	72.84	16.64	22.84	51.37	0.00	0.00	124.21	16.64	Dec	43.67
Dec	69.22	15.81	22.84	56.39	0.00	0.00	125.61	15.81	Dec	40.16
Total [kWh]	**2507.13**	**472.25**	**19.62**	**777.78**	**21.99**	**2.28**	**3284.91**	**494.24**		**Av.: 51.80**

Percentage saved in the first 30 m with anidolic system alone = 15.1 %

(method 3) will be used as it is a more realistic method dependent on the required interior luminance and independent of the exact lamp luminance available. In addition it corresponds to the average of methods 1 to 4.
For methods 1 and 2, more savings are obtained with stepped control of the lights than with dimmed control, as with stepped control, the savings due to the anidolic depend on whether the lamps could be switched down or not due to the daylight. Hence it can occur that the anidolic system can save more lighting energy with stepped control.
A discussion of the calculation differences is available in section 8.1

6.2.3 Extrapolation for the north portal

If bi-directional traffic exists then savings using an anidolic system can be achieved at the north portal as well. If uni-directional tunnels are considered, then the same logic applies to the north portal of the other tube. In the case of high mountains and sunny conditions, L_{20} for the north portal will be lower than that of the south portal as the portal surroundings will "see" the northern sky and their luminance levels (seen by a driver going south) will be lower. For high mountains therefore, the tunnel entrance will have lower L_{th} values and lower luminance values due to daylighting as the northern sky is less bright and there is mostly no direct sun entering the tunnel mouth.
Anidolic system alone: For lower L_{20} values, lower absolute savings (slightly > ½ of the south portal values) are probable (based on low L_{20} values for the south portal.) The overcast savings remain the same for both portals.
If one assumes that the sunny period contributes on average 80% of the yearly savings ($S_{anid,0}$) for the south portal, and the north portal savings are roughly 68% of the south portal savings for sunny conditions, one obtains the approximate estimation:

$$S_{anid,0,N} = 0.8 * S_{anid,0,S} * 0.68 + 0.2 * S_{anid,0,S} = 0.74 * S_{anid,0,S}$$

where $S_{anid,0,N}$ are the savings in [kWh/a] for a north portal and $S_{anid,0,S}$ for a south portal, due to an anidolic system when no sky is "seen" by the oncoming driver.

Therefore, as a very rough approximation, 3/4 of the savings for the south portal can be expected for the north portal.
Anidolic system and daylight: Lower absolute savings (> ½ of the south portal values) are possible for lower L_{20} values. Again the overcast results remain constant. Similar savings can be expected. The savings for the two portals are given in table 10.

Table 10: South and north portals of a tunnel surrounded by mountains: Yearly savings for the anidolic system alone with stepped or continuous dimming of the lamps and for an anidolic system including the "free" daylight, with $S_{anid,0,N} = 0.75 * S_{anid,0,S}$.

Method	**Yearly savings [kWh/a]**		
	Anidolic_step	**Anidolic + daylight_step**	**Anidolic_dimmed**
1. L20 distribution [kWh/a]*	917	2604	765
2. Sum of monthly values [kWh/a]_1*	1099	2875	1017
3. Sum of monthly values [kWh/a]_2**	865	3131	868
Average of 2 and 3 [kWh/a]	982	3003	943
Average of 1 to 3 [kWh/a] *	960	2870	883
Cost savings for method 3 [Fr-/a] *	112	407	113

* based on artificial lighting luminance ** based on required threshold luminance

6.3 Tunnel with 24% of the driver's field of view consisting of sky considered when from a safe stopping distance. No mountains above the tunnel entrance

6.3.1 Hourly and daily energy savings

Figure 8 shows the tunnel road luminance in May as a function of tunnel depth for a tunnel with no mountains above the tunnel entrance. As mentioned above, the required threshold luminance is high (92 cd/m²) as the driver "sees" a bright sky, and L_{20}, hence L_{th}, depend on the area weighted luminance in the 20° cone. Some of the radiation from the northern part of the sky, which is no longer obstructed by any mountains, can be reflected by the anidolic scoop into the tunnel, either spectrally or (in a small percentage) diffusely. Hence, the interior road luminance with an anidolic scoop is slightly higher if there are no mountains than if high mountains exist above the tunnel.

Only one method was applied to calculate the daily, monthly and yearly electricity savings for the situation with sky "seen" by the driver. The summation method, based on the threshold luminance, which is a more correct, and also a more conservative method was used. Table 11 shows the daily results for March 21st.

Table 11: Daily savings due to an anidolic system alone and an anidolic system plus "free" daylight for clear sky conditions with sun on March 21st. The calculations are based on the required threshold luminance L_{th}. (DL: daylight).

hour [h]	step: saved electricity with anidolic [W]	step: saved electricity with anidolic [%]	step: saved electricity with DL & anidolic [W]	dimmed: saved electricity with anidolic [W]	L_{20}] [cd/m^2]	type of lamp scenario
9.00	150	9.4	775	199.4	1374	T2 - 1;0;0
10.00	500	18.5	1075	396.6	1276.5	U23-0.5,0.5,0.25
11.00	675	25	1000	562.1	1467.7	U23-0.5,0.5,0.25
12.00	550	21.2	1425	574.8	1610.7	T3 - 1/2;1;0
13.00	550	21.2	1425	487.2	1574.2	T3 - 1/2;1;0
14.00	500	18.5	825	514.2	1484.7	U23-0.5,0.5,0.25
15.00	500	18.5	1075	470.25	1303.1	U23-0.5,0.5,0.25
16.00	325	20.3	1025	289.8	1028.8	T2 - 1;0;0
average		**19.1**			**1390.0**	
total[kWh]	**3.75**		**8.625**	**3.49**		

6.3.2 Yearly energy savings

Table 12 give corresponding results to table 7 for the case without mountains above the tunnel.

Table 12: Monthly and yearly electric energy savings for lighting, for a tunnel with no mountains above it, with an anidolic system and stepped control of the lamps. The calculations are based on the required threshold luminance L_{th}.

Month	sun: savings [kWh]	overcast: savings [kWh]	total energy savings per month [kWh]	based on daily energy of	sunshine probability
jan_snow	34.40	31.44	65.83	jan_snow	40.35
feb	50.55	8.71	59.26	march	48.14
march	61.83	8.71	70.54	march	53.19
april	60.86	8.26	69.12	march	54.1
may	68.09	20.22	88.31	may	51.68
june	98.77	19.00	117.77	june	54.6
july	81.51	15.96	97.47	may	61.87
aug	68.62	7.62	76.24	march	59.03
sep	65.48	7.52	73.00	march	58.2
oct	65.77	8.08	73.85	march	56.58
nov	21.62	3.38	25.00	dec	43.67
dec	20.54	3.71	24.25	dec	40.16
total [kWh]	**698.04**	**142.61**	**840.65**		**51.80**

Initially one thought that maximum savings would be possible with a low threshold luminance (L_{th}) and maximum daylight entering the tunnel, as in the case with high mountains. However, the possible savings depend on: the threshold luminance, the available daylight with an anidolic scoop and the artificial lighting in a complex manner and this leads to different results as foreseen. More savings are possible with 24% sky in the driver's field of view as with no sky visible. This is because the sky luminance seen by the driver is high, leading to higher access zone luminance L_{20} and higher L_{th}, hence lamps with more power (higher luminous output) are needed to provide the threshold luminance. If the outputs of such lamps are reduced in steps (step control of the lamps), (e.g. to half of their maximum power), the savings will be bigger than with lamps having lower wattage. In addition, when there are no mountains above the tunnel, extra daylight originating from the northern segment of the sky can enter the tunnel after reflection from the anidolic scoop, as mentioned before. More absolute electricity savings are therefore possible as well as higher percentage savings (15% and 23% respectively) despite the increased lamp wattage (tables 9 and 13).

If the driver's speed is increased (such as on motorways) then so are: the "safe stopping distance"; the amount of sky "seen" by the driver and L_{20}; k and L_{th}. This implies that more artificial lighting will be required and hence lamps with higher wattage are needed. The ratios of L_{20} for the tunnels in case 2 to that in case 1 are 1.4 and 1.5 for June and March. On a yearly basis, the savings with an anidolic system at the south portal with no mountains are about 1.7 times higher than those with high mountains surrounding the tunnel south portal. Table 13 gives the yearly savings for both cases and corresponds to table 9 in section 6.2.2.

Table 13: South portal: Yearly savings for both tunnels (with and without mountains) for an anidolic system alone with either stepped or dimming lamp control and yearly savings for an anidolic system with "free" daylight.

Method	Yearly savings [kWh/a]		
	Anidolic_step	**Anidolic + daylight_step**	**Anidolic_dimmed**
0% sky in driver's view			
1. L20 distribution [kWh/a]*	524	1488	437
2. Sum of monthly values [kWh/a]_1*	628	1643	581
3. Sum of monthly values [kWh/a]_2**	494	1789	496
Average 1 – 3 [kWh/a]	549	1640	505
4. L20 distribution [kWh/a]** [kWh/a]	371		
24% sky in driver's view			
5. Sum of monthly values [kWh/a]_2**	**841**	**2376**	**875**
% savings for method 5 [%]	**23**	**64**	**24**

* based on artificial lighting luminance

** based on required threshold luminance

6.3.3 Extrapolation for the north portal

- L_{moun}: The hills on either side of the tunnel "see" the northern sky hence they have lower luminance levels than in the south portal case for sunny conditions → L_{moun} is very low.
- L_{fields}: The fields "see" mainly the northern sky but some southern sky as well hence their luminance is lower or similar to that of the south portal case.
- L_{road}: The situation with respect to the daylight is similar to L_{fields}. L_{road} is very high however due to the reflectivity of the material used.
- L_{sky}: The driver "sees" the southern sky now, which is bright, so that L_{sky} is higher than in the case of the south portal and very high when the driver looks in the sun's direction.

$L_{20} = 0.24\ L_{sky} + 0.28\ L_{road} + 0.29\ L_{moun} + 0.02\ L_{fields}$:

Assuming that L_{road}, L_{fields} and L_{moun} (where the latter two are negligible) are all lower for the north portal than for the south one, then the dominating change is for L_{sky}. Therefore L_{20}, and L_{th} will be higher for the north portal, requiring other lamp scenarios to provide the required luminance L_{th}. However, the northern sky provides much less daylight for saving electricity.(see figure 2).and it will be difficult to have sufficient daylight to switch the lamps down by a step (1/4 or 1/2 etc.). Continuous dimming would probably be better.

Therefore one should assume lower savings for a north portal (0.6 of the south portal savings) and a ratio of 76% between savings due to the sun contribution and the overcast contribution. This gives the following savings for the north portal, assuming the total south portal savings are $S_{anid\_24,S}$ for the relevant case and the savings are unchanged for overcast conditions:

$$S_{anid,24,N} = 0.76 * 0.6 * S_{anid,24,S} + 0.24 * S_{anid,24,S} = 0.7 * S_{anid,24,S}$$

where $S_{anid,24,N}$ are the savings in [kWh/a] for a north portal for the case when 24% of a driver's field of view consists of sky, as seen from a safe stopping distance.

Table 14: South and north portals of tunnels with and without mountains: Yearly savings for the anidolic system alone with stepped or continuous dimming of the lamps and for an anidolic system including the "free" daylight and stepped control of the lamps.

Method	Yearly savings [kWh/a]		
	Anidolic_step	Anidolic + daylight_step	Anidolic_dimmed
<u>0% sky in driver's view</u>			
1. L20 distribution [kWh/a]*	917	2604	765
2. Sum of monthly values [kWh/a]_1*	1099	2875	1017
3. Sum of monthly values [kWh/a]_2**	865	3131	868
Average 1 - 3	960	2870	883
<u>24% sky in driver's view</u>			
4. Sum of monthly values [kWh/a]_2**	1429	4039	1488

* based on artificial lighting luminance. ** based on required threshold luminance

In the case of the tunnel with mountains, the calculation results corresponding to the summation method based on the required threshold luminance in the tunnel entrance (methods 3 and 4 in table 14) will be used for further calculations and analysis as it is based on the luminance which has to be provided and not on the final luminance available due to the possible lamp combinations. For the tunnel without mountains the calculations are based anyway on the summation method and the threshold luminance, hence all further analysis is based on realistic values.

6.4 Yearly savings with anidolic systems for 148 Swiss tunnels

- The number of tunnels registered on main roads in 1991 was 78 bi-directional and 70 uni-directional [7].
- Knowing the number of tunnels with high mountains around the portal is really a study in itself, so that approximations have been made to obtain an order of magnitude for possible savings (see below).
- The powers installed, based on the first 30m of the entrances of the tunnels, are 0.1 MW/km and 0.16 MW/km for the two simulated tunnels. Lower average lamp power per kilometre will be obtained for the whole tunnel as the required interior luminance is much lower. The range of power installed for the studied tunnels [7] is 0.04 – 0.27 MW/km.
- For bi-directional tunnels, the lighting energy ranges from 7.7 MWh/a (Hemishofen) to 4899 MWh/a (Gotthard), or 66 MWh/a.km (Hemishofen) to 434 MWh/a.km (Lopper). For the tunnel Hemishofer the savings due to the use of an anidolic system would be ~<u>12%</u>, which is not negligible, whereas for the Gotthard tunnel the percentage savings would be absolutely negligible.

<u>Approximate calculations for the yearly savings for Switzerland:</u>

- Method 1: Out of the 40 registered bi-directional tunnels listed in [6], 21 have an altitude of over 850 m. Assuming that these are surrounded by mountains, and using the more conservative of the three methods to calculate hourly savings, then the savings due to the anidolic systems would be about 18.2 MWh/a (21 * 0.865). The remaining 19 would have savings ≈ 19 * 1.429 MWh/a, where 1.429 corresponds to the case without mountains. Extrapolating to the total number of bi-directional tunnels (78) gives 41 * 0.865 + 37 * 1.429 = 88.3 MWh/a (table 15).

- Similar calculations for the uni-directional tunnels (two tubes) above and below 850m give about 6*0.865 + 64 * 1.429 = 96.6 MWh/a (table 15). The total savings for the 148 registered tunnels are therefore about **185 MWh/a**.

- Method 2 : Another approximation could be that all bi-directional tunnels are located on normal roads with low traffic velocity (hence short stopping distances with no sky "seen" by the driver in the 20° circular field of view), hence corresponding to our "high mountain" case. All the uni-directional tunnels would be on highways with about 24% sky seen by the driver. Assuming that 2/3 of the tunnels are orientated south-north and 1/3 west-east (based on the Switzerland's general orientation) then, based on the approximations described in method 1); the savings would be:
  Bi-directional tunnels: 2/3 * 78 * 0.865 + 1/3 * 78 * 1.4[1)] * 0.494 = 63.0 MWh/a.
  Uni-directional tunnels: 2/3 * 70 * 1.429 + 1/3 * 70 * 1.4[1)] * 0.841 = 94.2 MWh/a, (table 15). Method 2 is an over pessimistic method as even with short stopping distances sky is "seen" by the driver if there are no mountains above the tunnel.

Table 15: Estimation of possible savings for the Swiss tunnels.

Method	**Type of tunnel**		**Total savings**	
	Bi-directional	**Unidirectional**	**[MWh/a]**	**[SFr.-/a]**
Method 1 [MWh/a]	**88.3**	**96.6**	**185**	**~24'000**
Method 2 [MWh/a] [1)]	63	94	157	20'430

[1)] To estimate E-W tunnels, one can proceed as follows: The distribution of L_{20} values per month and time (obtained from the simulations) can be used. As the portal facing E (or W) never "sees" a very bright sky anymore, values of L_{20} over 1000 can be ignored. If one uses table 6, then the savings per E (or W) portal are about 70% of the south portal. Hence we can assume 1.4 times the south portal savings per E-W tunnel.

- The savings of **185 MWh/a** correspond to the additional savings due to the anidolic system after the lamps have been already reduced in power to take advantage of the free daylighting (without anidolic system). This gives approximate savings of **SFr.-24'000**, if one assumes the electricity to cost 13 Rp/kWh.

- These are conservative estimates, (if the tunnels are assumed to have an orientation south-north), as there are surely a considerable number of tunnels (e.g motorways) where more than 24% of the field of view corresponds to sky luminance, giving higher savings. Higher vehicle speed means a longer safe stopping distance and more sky visible in the 20° cone, which means a higher value for L_{20}. A higher value for k (in $L_{th} = k * L_{20}$) leads to a higher required threshold luminance, L_{th}, and hence more artificial lighting and possibly more savings. This is an extrapolation which may not be exact as the interactions between available daylight, the lamp powers and steps in luminance to be exceeded to save energy are complex. Counterbalancing the argument concerning higher velocity is the fact that some tunnels will be west-east or vice-versa. A rough approximation[(1)] implies savings to be 70% to 80% of the south portal savings for the west or east portals. The savings for an east-west tunnel are therefore less than for a south-north tunnel. Hence using just the two tunnel cases (0% and 24% sky in driver's field of view) is not a bad compromise.

7 Economical analysis

7.1 Yearly cost of an anidolic system and the "equivalent cost of electricity" if an anidolic system is used

- Assuming the aluminium thickness for the anidolic system to be 0.5 cm outside and 0.1 cm inside, the area of the anidolic to be about 18.7 m^2 and the price of aluminium to be \$ 1500/ton, then:
  the price of the aluminium for the anidolic = Fr.- 294
  =~ **Fr.-16 / m^2**

- Assuming a factor of **4** for the production costs, then the price / m^2 is ~ Fr. 64.-
  Price of an anidolic system is =~ **Fr.- 1200**
  With an annuity for 15 years at 8% the anidolic cost = **Fr.- 96**

  The price of a new system is about 1/8 of the price of a solar collector. Making a aluminium bent sheet (like for a car) is much easier than combining various layers, including expensive glass, as in a solar collector.

- South portals with anidolic systems :
  For a tunnel with no sky in driver's view: savings = 494 kWh/a → ~ Fr.- 64.-
  For a tunnel with 24% sky in driver's view: savings = 841 kWh/a → ~ Fr.- 109.-
  This assumes the cost of electricity to be 13 Rp./kWh. Therefore the annual cost of the anidolic scoop (Fr.- 96) lies between the two possible savings (Fr.- 64 and 109). One therefore breaks even with an anidolic system at the south tunnel entrance. This gives a range of "equivalent lighting costs" for the anidolic system of 11 - 19 Rp./kWh for a production cost factor of 4.

- South and north portals with two anidolic systems per tunnel:
  For a tunnel with no sky in driver's view: min. savings = 865 kWh/a → ~ Fr.- 112.-
  For a tunnel with 24% sky in driver's view: savings = 1429 kWh/a → ~ Fr.- 186.-
  Similar calculations give the range of "equivalent lighting costs" as 13 - 22 Rp./kWh. These values are only slightly higher than normal electricity costs.

- A higher production cost factor will increase the yearly anidolic cost and the "equivalent lighting costs", so that the latter will exceed the actual normal electricity price (e.g. for a production factor of 5, the anidolic price is ~Fr.1500.-, the cost per year with an annuity of 8% is Fr.-120.- and the "equivalent lighting costs" range is about 14 – 28 Rp./kWh), making the addition of an anidolic system less economical whilst the actual electricity prices subsist.

- The anidolic "equivalent lighting costs" are however well below the cost of electricity produced by renewable energy methods such as photo-voltaic panels (~1 Fr.- /kWh). There is in fact a factor of about 5 between them.

8. Discussion

8.1 Calculation methods

- The first method, which is based on a frequency distribution, is completely different from the summation methods. It is a combination of the frequency distribution for L_{20} calculated by the Swiss Office of Metrology department [9] for the tunnel in question and the average savings related to each L_{20} range, based on calculations with Radiance made at the EMPA.
- The first summation calculation method is based on the variable luminance levels provided by the lamps, L_{lamp}, as a function of the tunnel depth. The luminance levels corresponding to different lamp scenarios, with step control of the lamps, have increments in luminance levels between them of 10 cd/m^2 or more. Hence the artificial lighting luminance will either be equal or higher than the required threshold luminance in the tunnel portion where daylight has already partially decreased. At the entrance of the tunnel the lamp luminance is lower than the threshold luminance as sufficient daylight is entering into that part of the tunnel and contributing to the total luminance. The savings were calculated relative to the required threshold luminance L_{th} for this region. The second summation calculation method is always based on the required threshold luminance in the tunnel. The first summation method gives higher savings due to the anidolic system alone because of the higher interior artificial lighting luminance used as basis and consequently the bigger differences in luminance which can be covered by redirected daylight. However these savings depend on the lamps used, therefore the results obtained with the threshold luminance as basis should be used as conclusive results and in the economic analysis and discussion. If the savings calculated with the second summation method are used with the frequency distribution method then the savings are even lower (371 kWh/a), due to low saving being associated with high frequency values of the access zone luminance (L_{20}) range (see figure 6).
- The first considered tunnel with high mountains and the chosen anidolic system is not an optimal solution but a typical example for a sunny mountainous region. Optimisation of the tunnel choice remains a complex investigation due to the various interactive dynamic effects (such as daylight, sun position, adjustment of the lamps, location, vehicle speed etc.) which interact with one another. The second tunnel case corresponds to tunnels on normal roads in the lowlands and gives higher savings.
- The savings due to an anidolic system with dimming of the lights will not always exceed those with stepped lighting control as the latter depend strongly on which stepped position of the lamps is possible for the situation with daylight alone and how much the lights can be switched further down with the addition of an anidolic system.
- The yearly savings are interpolated using the calculated results of only one day per month and 5 representative months. The fact that August is represented by March is probably too conservative, giving slightly too low savings.

8.2 Eye adaptation

It would seem that the anidolic system can reduce eye adaptation problems. According to Robbins [5], the eye requires about 90 seconds for a 70% adaptation when the ratio between the exterior daylight level and interior daylight level is 200:1. The ratio decreases to 100:1 if the interior luminance level is provided by electric lighting. This implies that it is more difficult for the eye to adapt when the spectral composition changes as well as the intensity. The changes in luminance levels on entering the tunnel are definitely lower than those mentioned by Robbins. But it nevertheless follows that the anidolic system (without reduction of lamp output) works in three ways for the eye adaptation:

1. it increases the ratio of the interior "luminance due to daylight" to the "luminance due to artificial lighting" by bringing more daylight in;
2. it increases the overall luminance level;
3. it brings daylight further into the tunnel.

The final eye adaptation depends on the lamp strategy. If the lamp output is reduced to save energy, then the ratio "daylight : artificial light" is increased, but the overall luminance is decreased, hence the eye adaptation problem is only partially helped. If eye adaptation is a criterion, then it is probably better not to reduce the lamp power but aim at a maximum overall luminance level.

Introduction of an anidolic system can therefore be very advantageous for unlit tunnels in the mountains and for decreasing the eye adaptation problems at tunnel entrances where regular traffic jams exist, due to dense traffic and slow eye adaptation, such as in the Baregg tunnel (AG). In the case of traffic overloads at tunnel entrances, the loss of time and also money is enormous and any help to reduce such situations is worthwhile.

8.3 Usability of savings

- The anidolic system can either be considered to save lighting energy and/or to reduce eye adaptation problems.
- There are two effects in the threshold zone. Firstly, there is "free" daylight entering which increases the luminance levels. Secondly, there is an increase in luminance levels due to the capturing and redirecting of zenithal daylight by the anidolic system. It also results in daylight going deeper into the tunnel. Reduction of the lamp power and the related electricity savings due to an anidolic system are possible when the daylight luminance is less than the threshold luminance. In this region slightly lower total luminance will be available with an anidolic system and reduced lamp output, but the required threshold luminance L_{th} will be provided.
- For the tunnel with no sky visible in the driver's field of view, the additional percentage savings with an anidolic system for the section of tunnel where the anidolic system can be effective (30m) are **15%.** The corresponding percentage savings for the tunnel with 24% sky in the driver's field of view is **23%.** These are reasonable values. The problem which determines whether an anidolic system is financially worthwhile is the anidolic cost at the start.
- The absolute savings for the south portals of the two tunnels (0% and 24% sky in the driver's view) are small (**494** kWh/a and **841** kWh/a). However the "equivalent electrical costs" for an anidolic system range between 11 and 22 Rp/kWh and are less than that of a renewable energy "equivalent electrical cost". For example, the anidolic system is more economical than photo-voltaic panels which have an "equivalent electrical cost" of 1 Fr/kWh. Even with more stringent manufacturing costs for the anidolic system, for example doubled, the anidolic system remains more advantageous than PV panels. This implies that using anidolic systems in mountain tunnel, instead of only PV panels to produce electricity for the lights at the tunnel entrance, is a good option. One then saves expensive electricity produced by PV panels. This "PV" electricity, which is replaced by anidolic systems, is then free to be used elsewhere. The PV panels themselves can either be retained and used to illuminate the tunnel

interior, or one can merely rely on car headlights in the interior zone. In addition, the anidolic system can facilitates the eye adaptation at the tunnel entrance, due to an increase in the ratio "daylight luminance : electric lighting luminance". For mountain tunnels, where bringing electricity for artificial lighting is definitely too expensive, anidolic systems are also a solution.

- The savings of lighting energy, due to the addition of anidolic systems to both tunnel entrances, for a north - south orientated mountain tunnel have been shown to be 865 kWh/a. The savings for a tunnel where about a ¼ of the driver's field of view is sky are about 1430 kWh/a. Interpolating for the total Swiss tunnel situation (148 - assumed N to S - tunnels) indicates that up to 185 MWh/a or Fr 24'000/a.- can be saved. However, maybe only savings for south portals should be considered as those for north portals are less economical.
- If one considers the savings due to the anidolic system and the "free daylight" together, then the savings are considerable higher, and about 3 times those for the anidolic scoop alone (table 9) or 54%. Similar results are obtained for the tunnel without mountains (table 13). The savings are about 1800 kWh/a and 2400 kWh/a for the south portals of the two tunnels respectively.
- Higher savings are possible if the scoop area (daylight collecting area) is larger. This increase in savings can be estimated (appendix B). The scoop geometry is determined by the curvature of the tunnel and the space reserved for traffic. It also depends on the amount it protrudes outside the tunnel where its stability is important.
- Motorway tunnels have not been considered. Higher savings are probably to be expected as more sky can be "seen" by the driver, who has to have a longer safe stopping distance due to higher velocity, hence L_{20} is higher. If the vehicle speed is higher, "k" must have a higher value (in $L_{th} = k*L_{20}$) and therefore L_{th} increases as it is affected by both L_{20} and "k" [3]. More powerful lamps are required, probably allowing more savings. This situation has however not been simulated and the extrapolations may be incorrect.
- Further considerations are also necessary, such as: the construction problems, optimisation of the anidolic geometry, glare, the influence of dirt, pollution and snow on the outside scoop and the problem of cleaning the anidolic system generally. Possible solutions could be that snow be removed when the road is cleared of snow, and cleaning of the anidolic system could be foreseen to take place in conjunction with the lamp cleaning.

9. Conclusions

- The results are indicative due to the approximations made.
- The luminance level in a tunnel entrance can be increased and daylight sent deeper into the tunnel with an anidolic system placed at the entrance of a tunnel with a white ceiling.
- An anidolic system needs a white ceiling to operate. Substantial energy savings are already obtained with a white ceiling alone.
- If the electric lighting savings and the estimated cost of an anidolic system are considered, one breaks even financially with an anidolic system at the tunnel entrance.
- Introducing anidolic systems remains interesting:

  - If they can be produced cheaply (as in Australia),

- If they are compared to renewable energy methods, especially photo-voltaic panels,
- In the mountains, where bringing electricity is expensive, and the tunnels are either not lit at all or PV panels are used,
- Where helping eye adaptation is important, such as for reducing traffic bottlenecks,
- In the future, if the price of electricity increases or the general energy policy changes.

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Appendix A

Comparison between measurements and calculations of daylight factors in a tunnel entrance

1. Introduction

Comparisons were made between daylight factor measurements made in a scale model of a tunnel and the corresponding calculations made with Radiance. The measurements were effectuated in the artificial sky at the LESO-EPFL. A first set of comparisons exists for the tunnel without any daylight system and a second set with an anidolic reflector which was placed just above the "light volume" reserved for traffic at the tunnel entrance. The opening dimension of the anidolic system equals the capture depth (see sketch). (An anidolic system stretching completely across the tunnel mouth but slightly higher above the "light volume", with a narrower daylight capture depth – and smaller area - has also been simulated.

2. Measurements

Scale models of the „Jonerwald" tunnel near Zürich were built at the EMPA, with dark or white walls. The daylight factors in the tunnel were measured for an overcast sky and a clear sky without and with sun on the following days at the given times: March 21st, June 21st and December 21st at 5.00, 9.00, 11.00, 12.00 and 16.00.

- In figure 1, one sees the daylight factor (DF) variation according to sun position. The DF drops below 50% at the tunnel entrance facing north as soon as the bright sky area surrounding the sun is no longer "seen" from the tunnel entrance (solar azimuth < 90°).
- The illuminance values in the artificial sky are clearly smaller for the north facing portal than for the south facing one (figure 2), so that a south facing portal has a higher potential for saving artificial lighting.
- Between about 2m and 5m tunnel depth, the white walls improve the daylight road illuminance for overcast and clear skies in March, but are less effective for high solar angles as daylight in the tunnel falls off very sharply in this situation. White walls increase visibility when artificial lights are switched on.
- The measurements show that the daylight factors are highest with a specular anidolic system combined with a specular ceiling, compared to a specular anidolic system alone, a grey non-specular anidolic system or no anidolic system at all (figure 3). The increase in horizontal DF in the tunnel with a specular ceiling and specular anidolic system is most prominent for a clear sky with sun (figure 4). The increase is also high for June 21st at 12.00, but here the direct sun is being blocked by the anidolic system in the artificial sky, so that the results look like those for a higher sun position. (See below for further discussion.) The vertical illuminance values are highest in March (lower solar position).

3. Comparison without any daylight system

The measurement results (described above) and the calculation results (simulated with Radiance) for the horizontal sensors for both overcast and clear sky conditions (either without or with sun) were very close (figures 5 and 6). For both overcast and clear sky without sun the daylight factors drop from about 50% (60% for a clear sky) to about 10% in 5 meters. If vertical sensors are considered then a greater discrepancy between measurements and calculations is observed, especially at 10 m depth for both overcast and clear sky without sun. As subsequently, road luminance values are required, ("seen" from the driver's position), the simulations are acceptable.

4. Comparisons for anidolic system

The anidolic system is positioned above the tunnel volume reserved for traffic. Partly due to technical constructional reasons and partly to reach a larger capture area, the anidolic scale model was reduced in width compared to the previously studied system, so that the capture area, depth and opening were larger. Different geometry and sizes of anidolic systems give slightly different illuminance values as a function of tunnel depth (see simulations).
The comparisons between the measurements and simulations of daylight factors were acceptable for overcast sky and clear sky without sun conditions (figures 7 and 8). The simulation results are slightly higher than the measurements. This could be due to the reflection coefficient of the anidolic parabola, whose surface was relatively rough making the reflection coefficient difficult to measure. A slightly modified input – variation in 'rtrace' - gave even better results for the overcast sky comparison. Problems arose for a clear sky with sun (figure 9), where the "solar daylight factor" is the ratio of interior illuminance to exterior illuminance for that hour in question. On June 21st at 10.00, the results are very similar. This is not the case for the 12.00 results where direct sun rays are blocked by the anidolic system in the measurements and can enter the tunnel entrance in the simulations. The latter would seem to be correct. The problem is probably due to the rather large lamps used to simulate the artificial sky. The sun is simulated by increasing one lamp's power by a factor of 70, but the position of the lamp may not be exactly that of the sun, so that sunlight from the artificial sky can be blocked by the anidolic system, whereas it just passes in reality and in the simulation (figure 9). This obviously causes large differences in the results at the entrance which have repercussions deeper in the tunnel.

5. Simulations

Simulations show that for both horizontal and vertical values of illuminance at 20m depth a narrow anidolic system is very slightly better. If luminance values are considered, then the narrow anidolic system is slightly better along the tunnel depth for overcast conditions (which exist 50% of the time roughly in Switzerland). Sunny conditions favour the wide anidolic system up to 30m, where there is sufficient daylight with an anidolic system anyway, but deeper in the tunnel both systems are equal. Although the "wide" anidolic system has a larger capture area its length across the tunnel is smaller. The part of the anidolic system near the tunnel entrance with its given curvature (see figure 3 in the main report) is probably of importance for an overcast sky and will be smaller with the "wide" anidolic system and hence less efficient.
Simulations of the luminance across the tunnel, at 30m depth, show fairly constant values for an overcast sky, whereas the values increase on the west side as the sun is about 7° east of the south direction at 12.00.

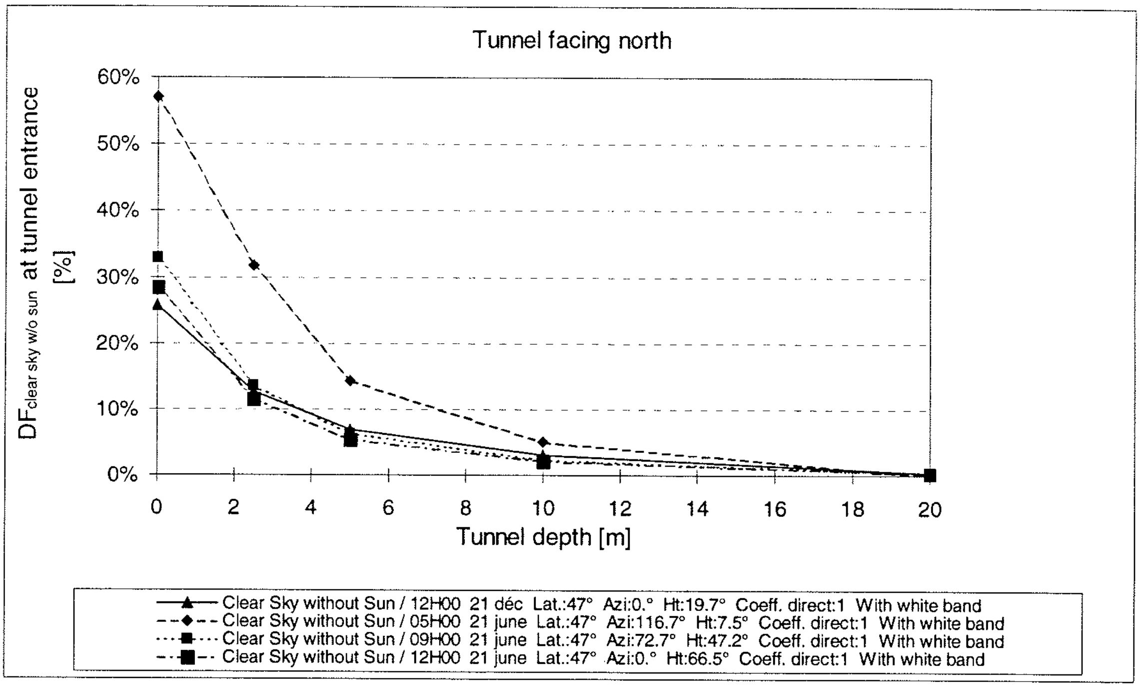

Figure 1: Measurements: daylight factors for the north facing tunnel for different sun positions.

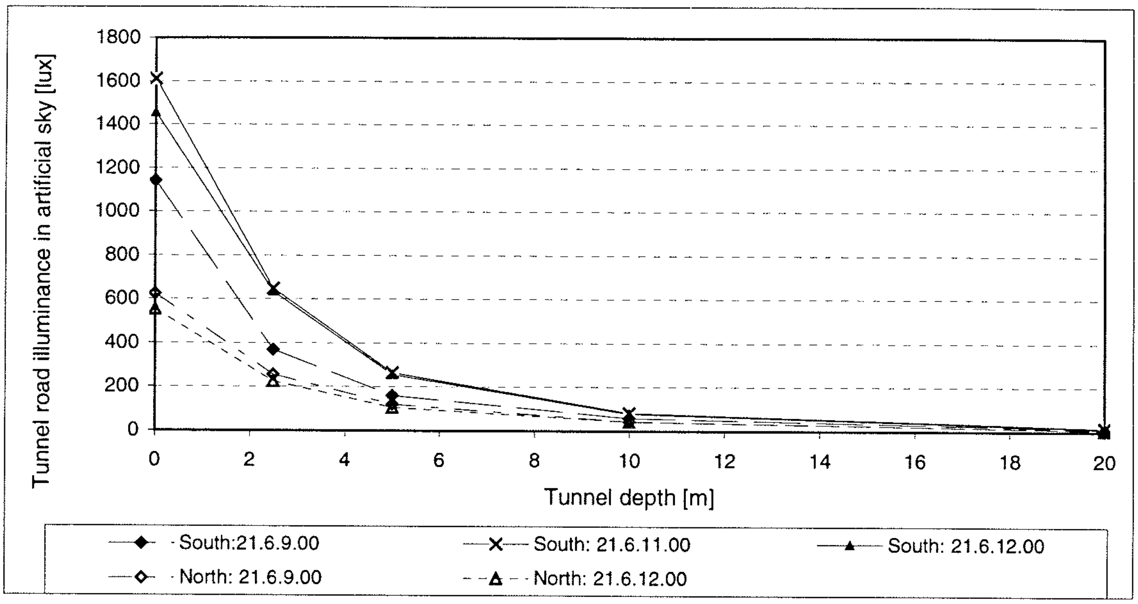

Figure 2: Measurements: illuminance values for south and north facing portals

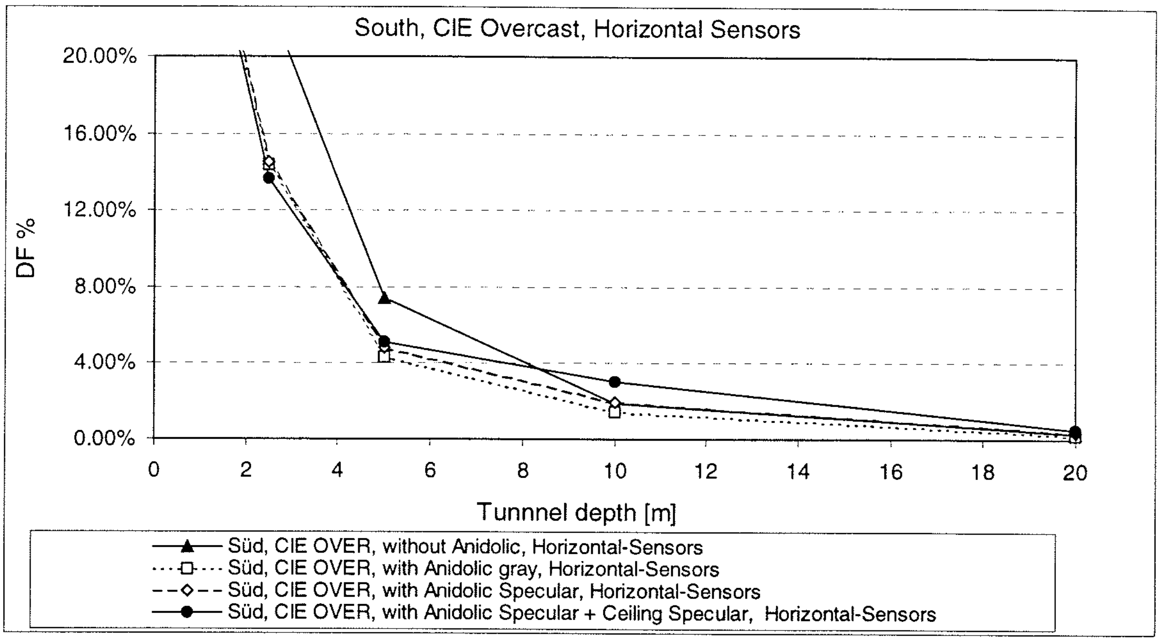

Figure 3: Measurements: comparison between no anidolic, grey anidolic and ceiling, specular anidolic and specular anidolic and ceiling for overcast conditions.

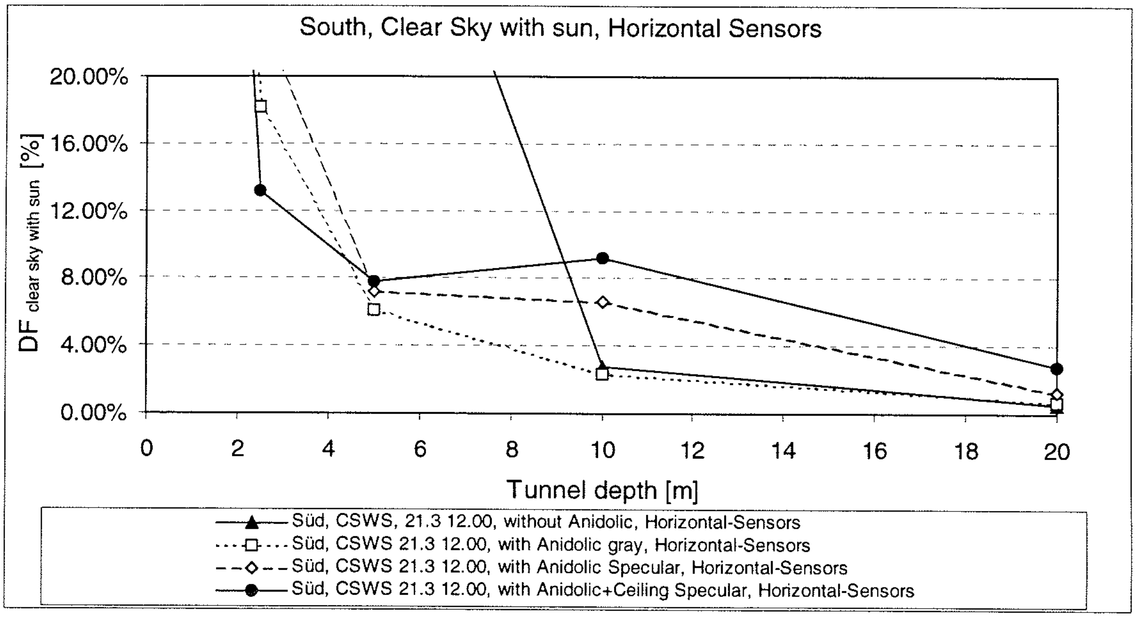

Figure 4: Measurements: comparison between no anidolic, grey anidolic and ceiling, specular anidolic and specular anidolic and ceiling for a clear sky with sun.

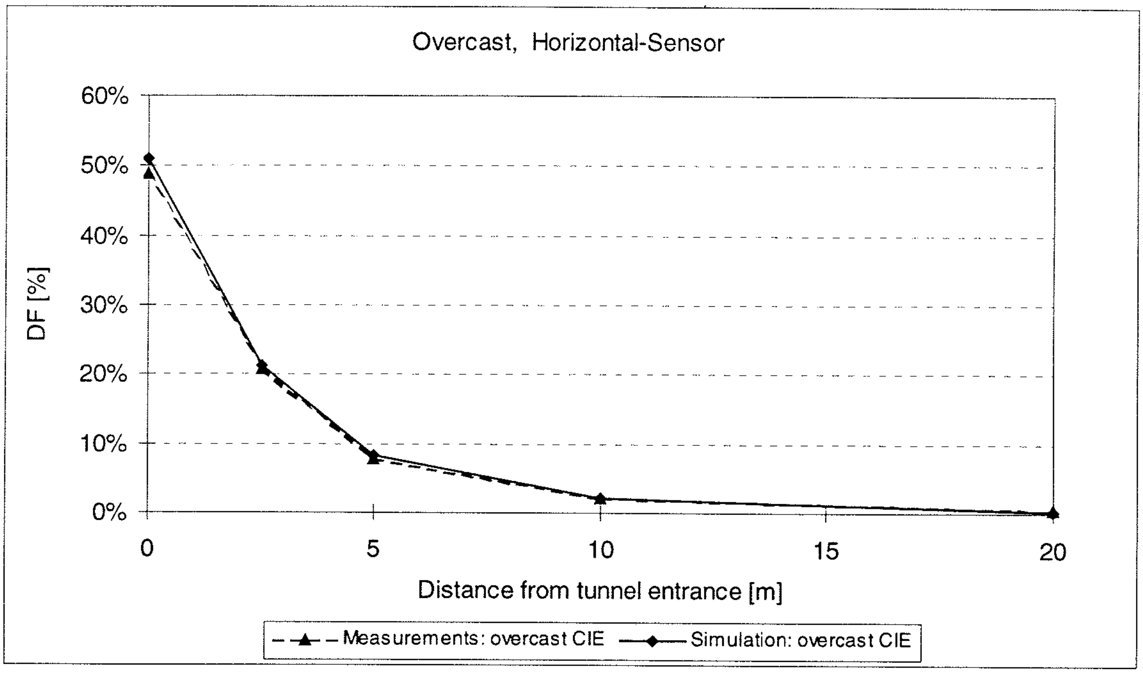

Figure 5: Comparison of measured and simulated daylight factors (DF) for overcast conditions.

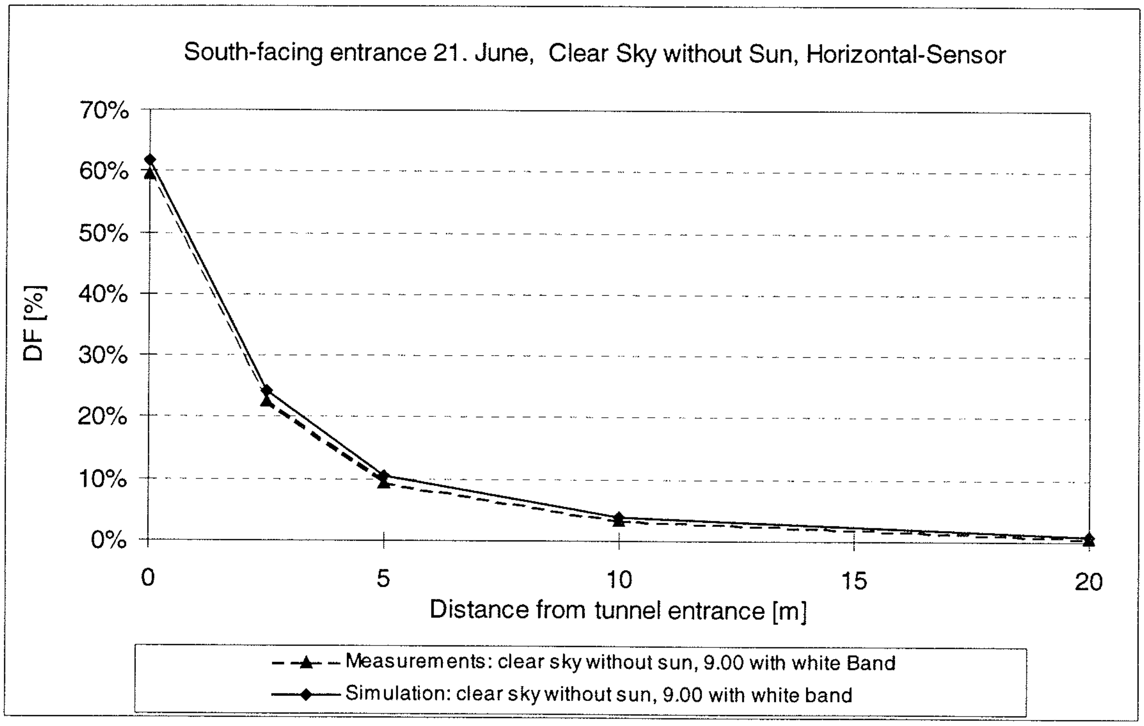

Figure 6: Comparison of measured and simulated daylight factors (DF) for a clear sky without sun

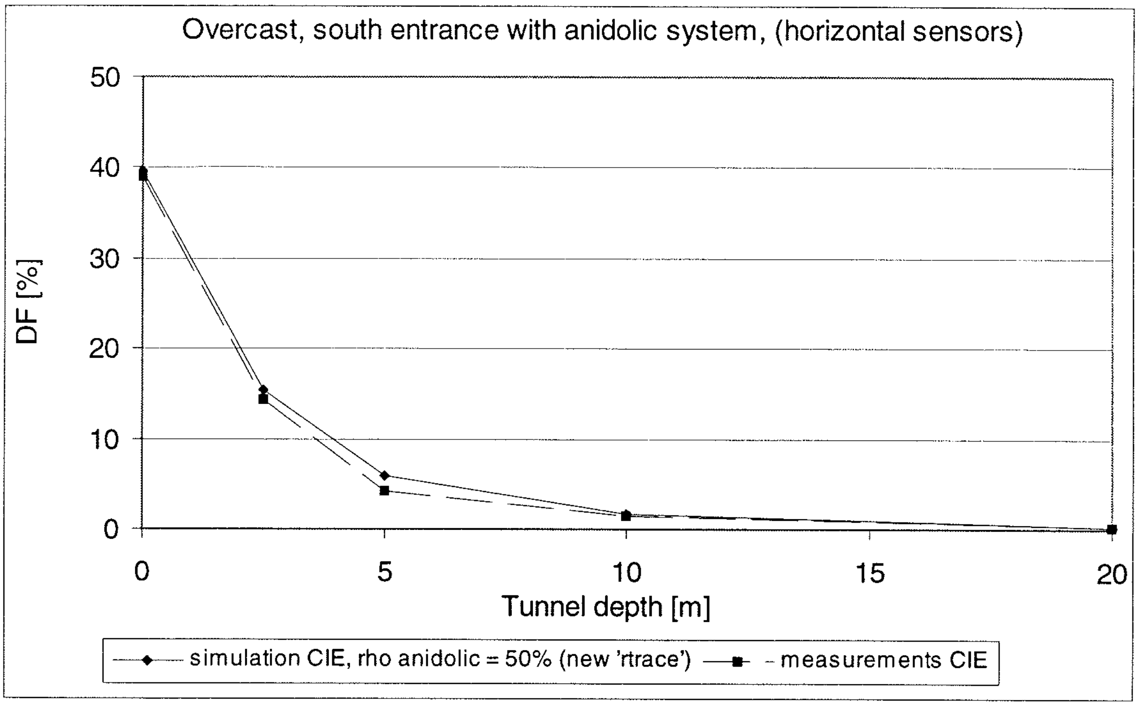

Figure 7: Comparison of measured and simulated daylight factors for the tunnel with anidolic system for an overcast sky.

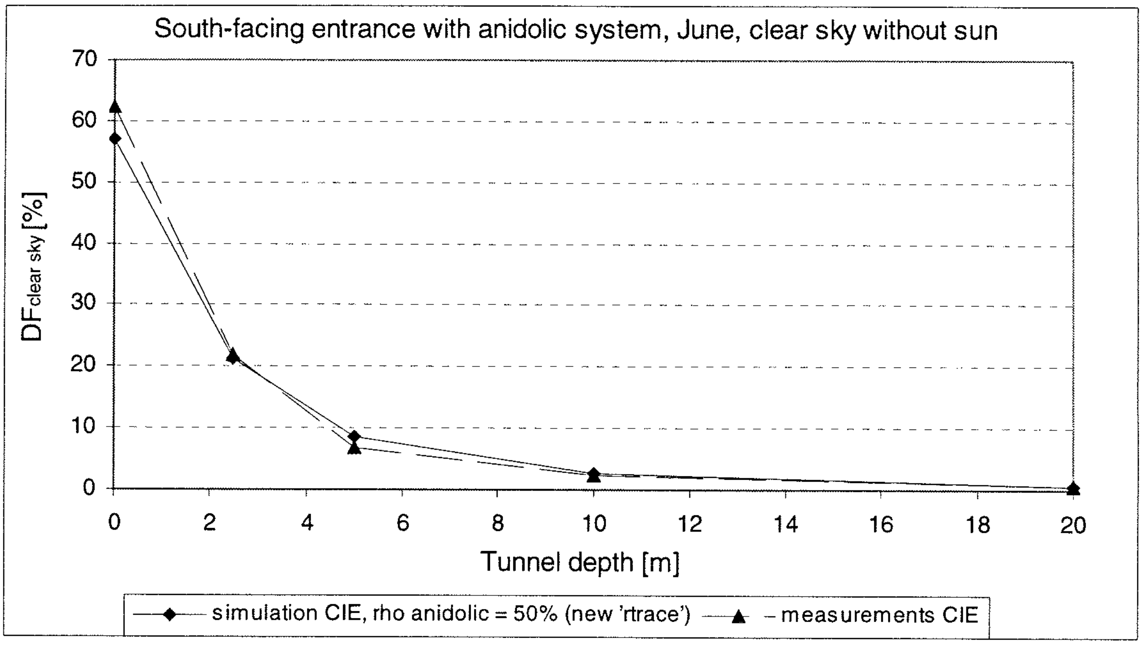

Figure 8 : Comparison of measured and simulated daylight factors for the tunnel with anidolic system for a clear sky without sun.

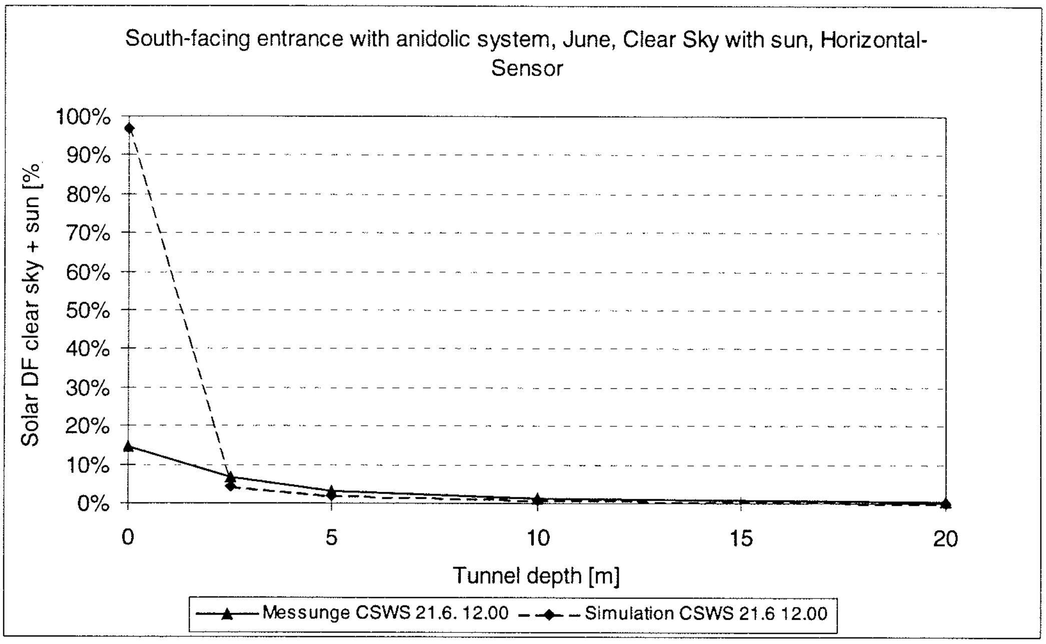

Figure 9 : Comparison of measured and simulated daylight factors for the tunnel with anidolic system for a clear sky with sun (CSWS. Clear sky with sun).

Appendix B

Auxiliary simulations

1 Luminance as a function of the road width and consequences on the method of simulation

The luminance results across the tunnel width were asymmetric for both the overcast and clears sky with sun conditions at 12.00. It turned out that for the Radiance calculations, the accuracy depends on the luminance values at the start of the calculations. In order to obtain a higher accuracy, the luminance values at the start need to be low and increase as the calculations proceed. This means starting the calculations at 50m depth in the tunnel and proceeding towards the exterior. Up till then the reverse had been done. All simulations used for the energy savings were therefore effectuated starting deep in the tunnel.

2 Anidolic system dimensions

Both anidolic system considered were placed above the area reserved for vehicles. The "low" or "narrow" case was 80 cm high and 6 m wide (see figure 3 in report), whereas the "high" case was 160 cm high and 4 m wide. This means that the anidolic scoops protruding outside the tunnel were 80 and 160 cm deep respectively with "collecting" areas of 4.8m^2 and 6.4m^2 (33% increase).

Overcast skies: The "narrow" system (smaller scoop) was very slightly better for the road section extending from the entrance to a depth of 50 m (figure 1). A possible explanation is : for the larger (deeper but less wide) scoop, diffuse daylight from the zenithal part of the sky (higher luminance) hitting the scoop section further away from the portal may well be reflected back to the sky and not into the tunnel; whereas the smaller (less deep but wide) anidolic system could reflect practically all incident diffuse daylight into the tunnel. The narrow anidolic scoop gave higher luminance values on the vertical walls.

Clear sky with sun: The system with a larger collecting area gave higher luminance values than the one with smaller collecting area (53 % or 5.7cd/m^2 more at 25 m depth) for sunny conditions at 12.00 in June. (This was valid for the section from the entrance of the tunnel to a depth of 35 m. After this point the results were inverted.)

Finally, the system with smaller collecting area was chosen; firstly because the scoop part protruding outside the portal was less deep and hence more stable, and secondly due to its better performance for overcast conditions. The anidolic system with a larger collecting area is better for sunny conditions. However, one can say now that results are available, that for the anidolic system alone, the energy savings due to overcast skies are only 25% of those with a clear sky with sun. Considering these results one can extrapolate the savings for larger collecting areas - A' – using the factor γ which can be

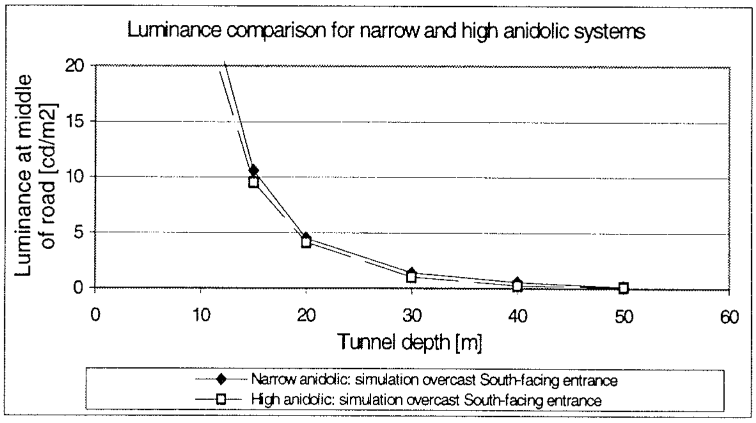

Figure 1: Comparison of dimensions for the anidolic system.

estimated as follows: $\gamma \cong (A' / 4.8) * 0.75$. 0.75 is used instead of 0.8 as a conservative value.

3 Dark and white ceiling for the tunnel entrance

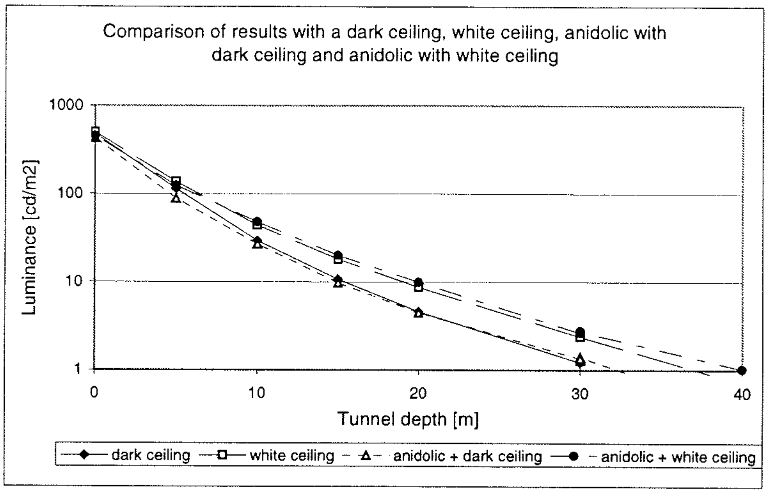

Figure 2: Overcast sky: comparison of the tunnel road luminance with different ceiling reflection coefficients with and without anidolic system.

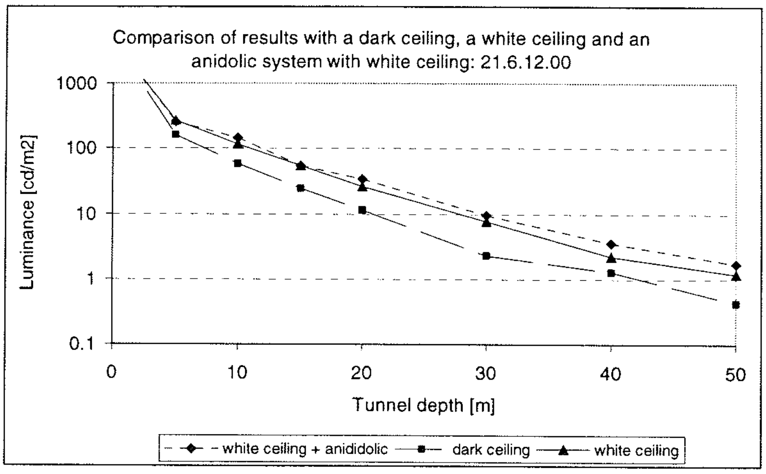

Figure 3: Clear sky with sun: Comparison of tunnel road luminance with different ceiling reflection coefficients and an anidolic system.

The dark ceiling corresponded to the actual situation in Jonerwald tunnel ($\rho_{ceiling}$= 0.268). Figure 2 shows that adding an anidolic system to this situation brought very little or no improvement for the 21st of June at 12.00 for an overcast sky. The situation for a clear sky with sun (figure 3) is similar but the differences due to the anidolic are more pronounced (about 6 times higher) for a south facing portal, which "sees" a high sky luminance. (The sky luminance "seen" by the driver is much lower as it corresponds to the northern segment of the sky.) Therefore a white ceiling ($\rho_{ceiling}$ =0.827).improved the luminance in the tunnel considerably from the mouth of the tunnel onwards. Adding an anidolic system to the tunnel with white ceiling reduced the luminance near the entrance and increased it compared to the white ceiling situation afterwards. This is what is required: a shifting of the daylight further into the tunnel. However the effect of the much brighter ceiling is greater than that of the anidolic system, but the optimum is with both combined.

4 High and low mountains without and with an anidolic system

High mountains surrounding the tunnel portal means that no sky is "seen" by the oncoming driver travelling north, so that the mean outside luminance of the tunnel entrance as seen the drivers (L_{20}) and consequently the required interior tunnel road luminance values (L_{th}) are low. This is because the sky luminance (L_{sky}) is higher than the surrounding luminance ($L_{surrounding}$). The portal faces south, with a maximum of daylight entering the tunnel so that the saving potential should be a maximum. However, in the case of low mountains, daylight from the northern section of the sky can be reflected into the tunnel, after reflection from the road (ρ_{road} = 0.187) (figure 4). In this case, the mean outside luminance of the tunnel entrance (L_{20}) and the required interior tunnel road luminance (L_{th}) are also definitely higher as a portion of sky is "seen" by the driver.

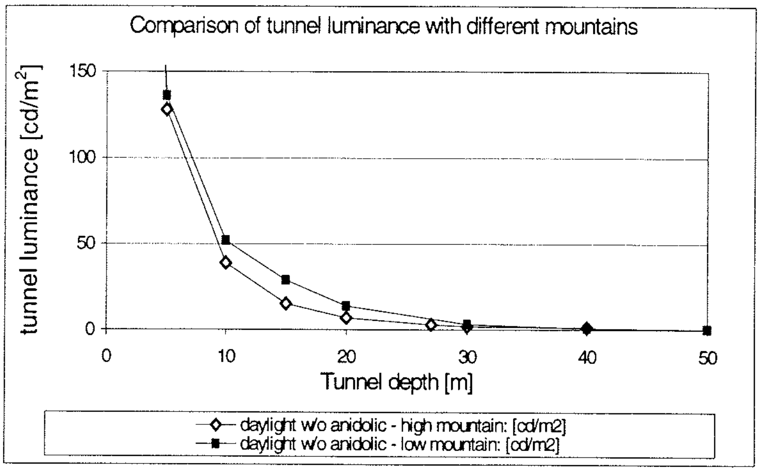

Figure 4: Comparison of interior luminance levels with different mountains.

5 Reflection coefficient of the mountains

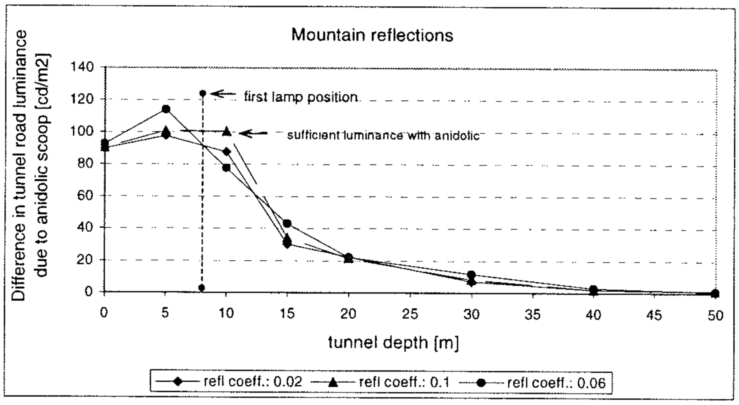

Figure 5: Sensitivity analysis for mountain reflection coefficient.

The reflection coefficient of the mountains was taken to be 0.018 corresponding to dark fir trees. This is definitely lower than values for grass (0.06) and rock (0.2) and may produce rather low increases in interior luminance with an anidolic system as very little daylight is reflected from the mountains unto the scoop. Figure 4 shows a sensitivity analysis for the 21st of June at 12.00 with direct sun shining unto the mountains. Generally, mountains with a higher reflection coefficient cause a higher increment in luminance (Δ_{lum}) due to the anidolic scoop. Two effects are then acting in opposite directions : the luminance increment (Δ_{lum}) due to the anidolic scoop increases but the required interior road luminance (L_{th}) to be provided also increases. Without a complete yearly simulation with lighter mountains, it is difficult to extrapolate the tendencies.

6 View direction in tunnel

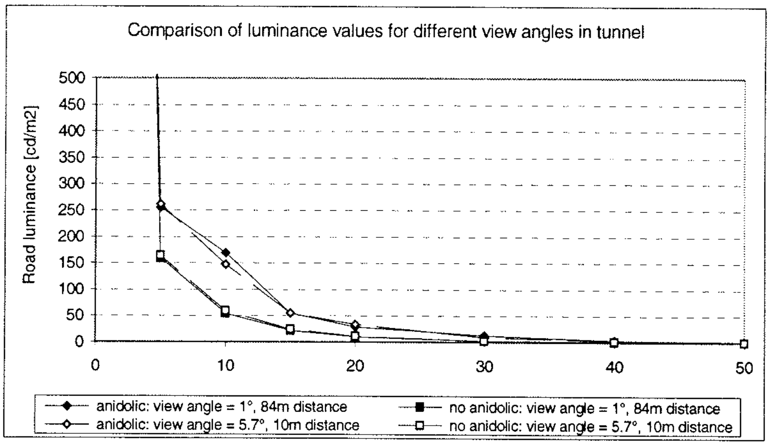

Figure 6: Sensitivity analysis for different view angles to calculate the luminance, which is dependent on the view direction.

The luminance calculations in the tunnel were made from a view point 1m high (driver position) towards a patch of road 10m away, making an angle of 5.7°. Luminance measurements of road samples are usually made with a view angle of 1° [8]. Figure 6 shows the luminance calculations with different view angles with and without anidolic system. Apart from the luminance values at a depth of 10m there are no significant differences. At 10m depth there is mostly sufficient daylight anyway, so that the differences in results with an angle of 5.7° and 1° are irrelevant.

7 Variation of interior luminance for different months

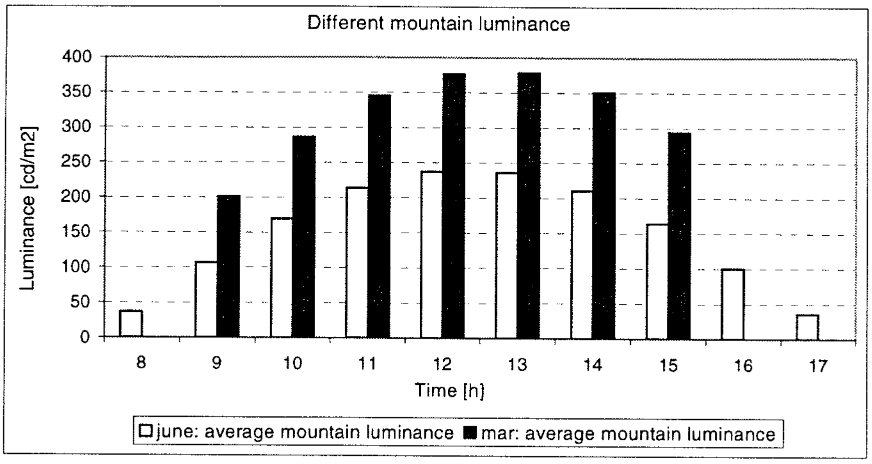

Figure 7 shows clearly the strong dependence of the mountain luminance on the month. It is therefore important to consider various months to estimate the yearly energy savings.

Figure 7: Mountain luminance levels during the day for June and March.