Analysis of tunnel lighting based on visual performance and visual comfort

Kai Sørensen and Dennis Corell; January 2019

Foreword and introduction

This work has been sponsored by NMF, which is a co-operation in the Nordic countries aiming at development and improvement of road equipment.

The purpose is to provide a tool for the analysis of tunnel lighting based on criteria for visual performance, visual comfort, the road surface luminance in the interior zone (optional) and a maximum value for the road surface luminance.

This tool is implemented in an excel file "Analysis of tunnel lighting based on visual performance and visual comfort".

The excel file and the above-mentioned examples may be useful for the revision of CIE 88:2004 by CIE TC 4-53 on tunnel lighting. Some members of the NMF are also members of CIE TC 4-53.

This report describes the excel file - how it works and its input and results. Some examples of use are included.

Section 1 describes how the excel file derives a profile of the road surface luminance of a tunnel, starting at the tunnel entrance and ending well inside the tunnel.

Section 2 accounts for the input values of the excel file.

Sections 3, 4, 5 and 6 explain how the above-mentioned criteria are used and how they interfere with the luminance profile.

Section 7 accounts for the main results derived from the luminance profile.

Section 8 gives an overview of the examples of use and a few tentative conclusions of comparison to CIE 88:1990 and CIE 88:2004.

A more detailed explanation of input values and results is found in annex A.

The examples are presented in annexes B and C. Those in annex B are general examples relating to the influence of the criteria and some of the important input values. The examples in annex C serve for comparison to recommendations in CIE 88:2004 and CIE 88:1990.

The excel file leans on some of the aspects of CIE 88:2004 and on uses the visibility model of Werner Adrian: "Visibility of Targets", Werner Adrian, Transportation research record 1247, http://onlinepubs.trb.org/Onlinepubs/trr/1989/1247/1247-006.pdf.

There are no claims to any of the methods and the excel file is available to anybody with an interest.

The criterion for visual comfort may be novel. It is thought of as an alternative to the concept of "adaptation" which seems to be a vague concept. There is a fairly long attempt to justify this criterion in section 4.

1. A drive simulated by the excel file

The excel file simulates a drive in daylight starting at a reference position, where the driver is one stopping distance in front of a tunnel, and ending well inside the tunnel. The drive is carried out a certain driving speed, and with a stopping distance associated with the speed.

The drive is carried out in steps with a uniform spacing of one tenth of the stopping distance, and in each step the driver looks at an object placed at the road one stopping distance ahead.

At each position of the object, the road surface luminance at the object is determined accordance with the input values including criteria for visual performance, visual comfort, an optional setting of the luminance in the interior zone and a maximum road surface luminance value.

Once the drive is completed, a profile of the road surface luminance has been determined, starting at the tunnel entrance, passing through the threshold and transition zones and carried on well into the interior zone.

A direct calculation of the luminance profile is actually not possible because of the complexity of the calculations. Therefore, it is necessary to determine the luminance profile in an iteration, where the drive is repeated a number of times. The profile of the first drive is based on an estimate, while the profiles of the following drives are adjusted to become correct in a gradual manner. The adjustments of the profiles are based on the criteria discussed in sections 3, 4, 5 and 6.

Examples of profiles in repeated drives are shown in figure 1. Already after drive No. 4, the profile is close to the final profile obtained in drive No. 20. This illustrates that the iteration converges quickly towards a final profile.

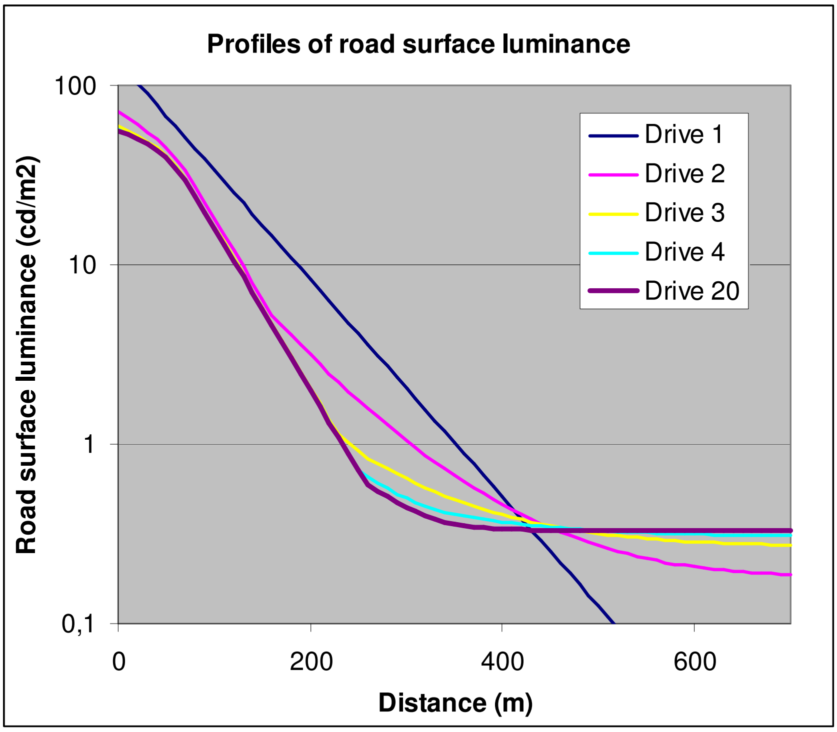


Figure 1: Example of profiles of road surface luminance in repeated drives.

The calculations are the same all through the drive. However, disability glare from daylight applies only for the threshold zone, which makes this zone special. There is no such clear distinction between the following transition and interior zones, where the road surface luminance decreases gradually towards a constant value

L_{in}. In practice, however, it is necessary to define the start of the interior zone by a higher value of the road surface luminance than L_{in}. The excel file uses the value of $1{,}2 \times L_{in}$.

All the calculations are done by the excel file. All that the user may notice is that the results are updated, whenever an input value is changed.

It is pointed out that the road surface luminance profile is described by a single value at each location. This implies that details relating to transverse locations of the object and the precise directionality of the lighting are not taken into account.

2. Input to the excel file

The input values include a driving speed, the age of the driver, the transmittance of the wind screen, the transmittance through the air, the size and the intrinsic contrast of the object, the duration of a glance of the object, various glare sources, and values for the criteria. The main input values are shown in figure 2.

Driving				Visual task		Disability glare			Criteria			
Design speed V	Driver age	Wind screen trans.	Air transmit-tance	Size of object	Intrinsic Contrast of object	Daylight total Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Time per factor 10 t10	Road surf. luminance interior zone Lin	maximum all zones
km/h	23-75 y	%	%	m	%	cd/m2		cd/m2		seconds	cd/m2	
80	60,0	80	100	0,2	-68	300	0,1	0,25	5,00	5		1000

Figure 2: Main input values.

The driving speed can be set to 60, 70, 80, 90, 100 or 110 km/h (the range can be expanded, if needed). Each driving speed has an associated stopping distance selected from national standards/regulations.

The age of the driver is in the range from 23 to 75 and is preset to 60 years. The transmittance through the wind screen is preset to 80 %. The transmittance through the air applies for one stopping distance, it is preset to 100 %.

In agreement with CIE 88:2004, the object is a vertical square surface with a preset size of 0,2 m and a reflectance of 0,2. Also in agreement with CIE 88:2004, the intrinsic contrast is preset to -68 %, as calculated for a lighting installation with a contrast revealing coefficient q_C of 0,2 (symmetrical lighting). An alternative value is -0,89 as calculated for a lighting installation with a contrast revealing coefficient q_C of 0,6 (counter beam lighting). However, all preset values can be modified.

There is a further input value, for the exposure time of the object as defined in the visibility model of Werner Adrian, which is set to 0,5 seconds. It has the effect of an apparent raise of the visibility level by approximately 17 %. This input is hidden in order to simplify the main input values.

In further agreement with CIE 88:2004, the glare at the reference position is caused by daylight and includes glare from the surroundings of the tunnel entrance (parts of the sky, the road surface in front etc.), glare from scattering in the air and from scattering in the wind screen of the car. The total of this glare is expressed by a value of the total equivalent veiling luminance L_{seq}.

To this is added a gradual decrease of the L_{seq} value as the driver approaches the tunnel.

Another glare source is the lighting installation itself, as described by the ratio between the L_{seq} value and the local road surface luminance at the drivers location. This value is preset to 0,1 corresponding to a threshold increment TI of approximately 10 %.

Other glare sources, for instance headlamps on opposing cars in a dual tunnel, are described by an additional L_{seq} value. This value is preset to 0,25 cd/m^2.

The criteria are discussed in the next sections.

There is a detailed account of the input values and their influence on the results in annex A.

Note: In the final version of the excel tool the amount of user adjustable inputs can be decreased as soon as there is an agreement upon input values that should be fixed, e.g. the size of the object and the intrinsic contrast of the object could be two such input values that could be fixed.

3. Criterion for visual performance

The criterion for visual performance is that an object, as seen on the background of the road surface, is visible with a minimum visibility level VL at each step. The visibility level is calculated in accordance with the visibility model of Werner Adrian.

The calculations include all the details of the visibility model - including the influence of the apparent size of the object, the background luminance, the intrinsic contrast of the object to the background, the influence of disability glare, the influence of the age of the driver, the exposure time of the object and positive/negative contrast.

A visibility level VL of 1 means that an object can be discriminated is otherwise good conditions. In practice, the VL value needs to be higher as a driver has several tasks to perform and cannot spend his full attention on small objects on the road. In his paper, Werner Adrian mentions that VL values of 10 to 20 may be needed. However, such values are impossible in tunnel lighting (and in road lighting). The VL value is preset to 5, which is a reasonable value.

The criterion is met by setting of proper values of the local road surface luminance at each location of the object. The road surface luminance at the tunnel entrance L_{th} is normally the highest followed by a gradual decrease towards a constant luminance in the interior zone.

This criterion is applied for all of the relevant zones: the threshold zone, the transition zone and the interior zone and has an influence on the road surface luminance in all of these zones.

The adjustments of the road surface luminance profile from one drive to the next in the iteration described in section 1 are done in the following manner. If, in one profile, the VL value at a location fails to comply with the minimum VL value, the road surface luminance in the next profile at the same location is rescaled in proportion to the two VL values (up/down when the VL value is too low/high).

4. Criterion for visual comfort

The criterion for visual comfort is that a minimum time must pass for a decrease of the road surface luminance by a factor 10. This time is called t_{10} in the following and is measured in seconds. It is preset to 5 seconds.

For the application of this criterion, the time interval between successive locations Δt is calculated by the excel file as the distance between successive locations divided by the diving speed in m/s. The permissible factor of decrease of the road surface luminance from one location to the next F_{10} is then determined as F_{10} = 10 to the power of minus $\Delta t/t_{10}$.

Example: A driving speed of 80 km/h equals 22,22 m/s. At an associated stopping distance of 100 m, the distance between successive locations is 10 m (with ten steps per stopping distance). Δt is therefore 10/22,22 = 0,45 seconds. With a value of t_{10} of 5 seconds, the ratio $\Delta t/t_{10}$ is 0,09 and the permissible factor of decrease F_{10} is $10^{-0,09}$ = 0,813.

At each location, two values of the road surface luminance are available. One value is determined on the basis of the VL value as accounted for in section 3, and the other as the road surface luminance at the previous location times the factor F_{10}. Whenever the road surface luminance calculated on the basis of the VL value is the lowest, it is replaced by the other value.

This means that the t_{10} criterion overrides the VL criterion, whenever the decrease of the road surface luminance would otherwise be too fast. This criterion is applied for all the locations, but has no effect for locations in the interior zone and only sometimes an effect for locations in the threshold zone. But the effect may be dominating for locations in the transition zone.

Whenever the t_{10} criterion overrides the VL criterion, there is a local raise of the VL value above the minimum.

This criterion interferes with the adjustments of the road surface luminance profiles from one drive to the next in the iteration described in section 1, but does not prevent that the iteration converges quickly.

The basis for this criterion is found in a paper by Duco Schröder: "The lighting of traffic tunnels, a paper presented at a meeting of the Shanghai Association for Science and Technology SAST, October 9 and October 12, 1987", https://www.swov.nl/sites/default/files/publicaties/rapport/r-88-18.pdf. It has statements like these:

"When considering the daytime entrance lighting, one must take into account one of the peculiarities of the visual system. When the visual system is adapted in a steady-state to luminance values between 30 and 3.000 cd/m^2, adaptation to another value in this range hardly takes any time: it can be considered as being instantaneous. When, however, the steady-state adaptation level is higher than 3.000 cd/m^2, the adaptation takes time; for high values (over some 8.000 cd/m^2) it may take up to half a minute".

"After the threshold zone, the luminance may gradually decrease towards the tunnel interior in such a way that the light level is not below the (temporal) adaptation. Experiments have suggested that a reduction in luminance of a factor of 10 in about 2 of 3 seconds can be tolerated, although some discomfort may arise. The corresponding region is called the transition zone".

Both statements mention "adaptation" and state that adaptation is fast, in fact so fast that adaptation can be ignored.

One exception is mentioned, namely steady-state adaptation to luminance levels higher than 3.000 cd/m^2.

However, a "Research Project: Visual adaptation for tunnel entrance, Final report, November 2013", http://www.diva-portal.org/smash/record.jsf?pid=diva2%3A681869&dswid=1929, concludes that observers can adapt from steady-state levels of 6.000 or 8.000 cd/m^2 down to a level of 2 cd/m^2 in about 5 seconds on the average. That corresponds to t_{10} values of approximately 1,4 seconds and disproves the exception. Accordingly, it is assumed that adaptation can be ignored.

The issue is that the second statement by Duco Schröder mentions that discomfort may arise, when the luminance level is reduced very quickly. This is taken on face value, although is it uncertain why discomfort may arise. One guess is that drivers need to orientate themselves to circumstances that change quickly, and try to do that by discriminating as many features in the field of view as possible.

In any case, the requirement of a minimum t_{10} value is assumed to relate to visual comfort.

5. Optional criterion for the road surface luminance in the interior zone

It is recognized that the road surface luminance in the interior zone, as recommended in CIE 88:1990 and CIE 88:2004, may be selected by other criteria than those described above. Therefore, as an option, the desired value of L_{in} can be set directly.

When this is done, the excel file internally derives a new minimum value of VL that makes the road surface luminance in the interior zone equal to the input value. In order to obtain a smooth transition from the transition zone to the interior zone, this minimum VL value is also applied in the transition zone.

Apart from a change of the minimum value of VL in two of the three zones, this criterion does not interfere with the iteration described in section 1.

6. Criterion for maximum road surface luminance

The maximum road surface luminance is set to 1000 cd/m^2. It has the simple effect to override the other criteria whenever they may result in higher values. This would in particular be at locations in the threshold zone – notably the L_{th} value at the first location.

This criterion also interferes with the iteration described in section 1, but does not prevent that it converges quickly. On the contrary, the criterion ensures that the excel file works smoothly.

At locations where this criterion may set in, the road surface luminance becomes 1000 cd/m^2 and the visibility level falls below the input value.

The justification for this criterion is that tunnel lighting cannot provide very high road surface luminance values in any case.

7. Results

The main results are shown in figure 3.

Stopping distance		Road surface luminance			Visibility level VL				Length of zones		Time in	Lseq
actual	maximum	maximum	Initial	Interior	at tunnel entrance		in interior zone		threshold	transition	transition	surround
	at VL level		Lth	Lin	intended	actual	intended	actual			zone	300
m		cd/m2			agreement		agreement		m		seconds	k factor
100	267	1000	124	0,73	5,00	5,00	5,00	5,00	100	224	10,08	0,019

Figure 3: Main results.

These, and other results from an additional user part, are briefly discussed in the following. There is a more detailed account of the results in A.6.

7.1 The stopping distance

The main results include the stopping distance associated with the driving speed. It is included as a confirmation of the proper selection of the stopping distance associated with the driving speed.

A further result is a value for a maximum stopping distance, which is the limiting distance from which the object can be discriminated with the desired visibility level. In case the actual stopping distance is raised above this maximum, the criterion for maximum road surface luminance will set in and the visibility level will be reduced.

Such cases are relevant, as it is sometimes necessary to consider stopping distances that are longer than the maximum. The question is then if the result of a limited luminance and a reduced visibility level is useful.

One argument in favour is that without the criterion for maximum road surface luminance, the result would be a very high road surface luminance – which is not useful.

Another argument in favour is that the loss of visibility level may be small enough to be acceptable (for instance a reduction from 5,00 to 4,50). Additionally, it may be that old drivers can maintain the visibility level by reducing the driving speed a bit (for instance by 10 km/h) and that drivers younger than the preset 60 years may experience a sufficient visibility level. Examples are given in section 7.6.

7.2 The road surface luminance

For ease of comparison with other results, the maximum road surface luminance is provided as a copy of the input value for this criterion.

An important result is the initial road surface luminance L_{th} at the tunnel entrance. The value is mostly generated by the criterion for visual performance in view of the input values, but can be reduced by the criterion for maximum road surface luminance.

Another important result is the road surface luminance L_{in} in the interior zone. The value equals the input value for L_{in}, if this optional criterion is used. Else, it is generated by the criterion for visual performance in view of the input values.

7.3 The visibility levels

Two visibility levels are supplied for the tunnel entrance – the actual value and the intended value given as an input value.

Those two values are normally equal and, if so, this is confirmed by the statement "agreement". However, the first value will be smaller than the second value, if the criterion for maximum road surface luminance has been invoked. If so, the statement is changed to "disagreement".

In the same manner, two visibility levels are supplied for the interior zone – the actual value and the intended value. The intended visibility has the value computed by the excel file for an input value of L_{in}, when the optional criterion for L_{in} is used. Else it is the input value for the visibility level.

These two visibility levels should always agree and this should be confirmed by a statement "agreement". If, for some unforeseen reason, they should not agree, the statement is changed to "disagreement".

7.4 Results added for comparison to CIE 88:1990 and CIE 88:2004

These results include the length of the threshold zone (equal to the stopping distance) and the length of the transition zone. The latter is supplemented by the time it takes to drive through the transition zone at the actual driving speed.

Further, the k factor defined in CIE 88:1990 is provided. This is in order to obtain comparability to the recommendations of CIE 88:1990 for the threshold luminance. It is explained in A.6.5 how this value is obtained.

7.5 Other results

The results also include diagrams with profiles for the road surface luminance and the VL values. See figure 4.

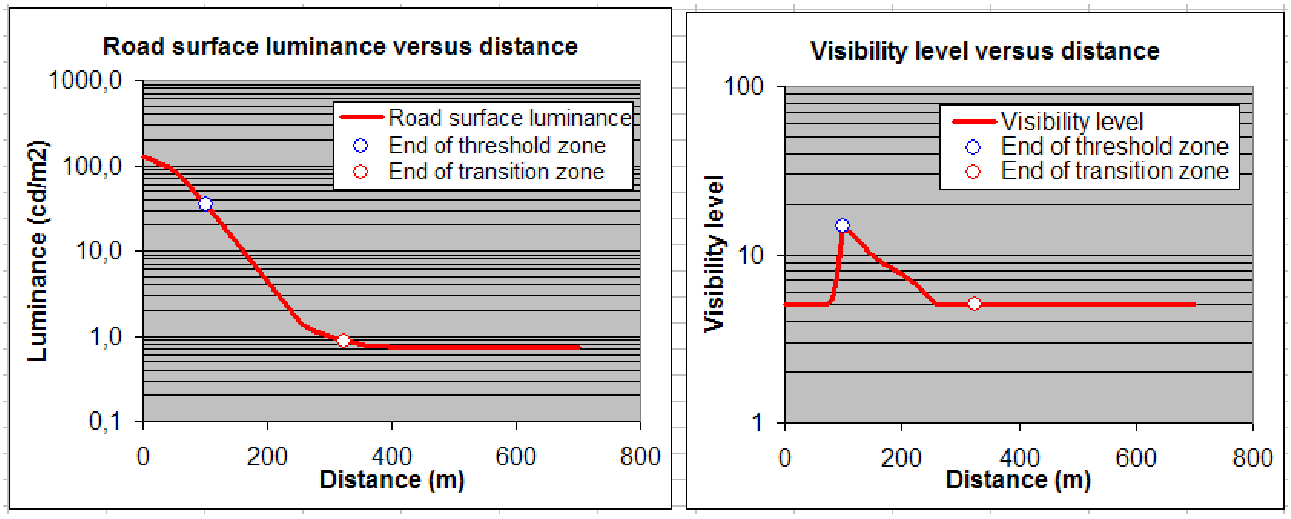


Figure 4: Diagrams with profiles for the road surface luminance and the VL values.

The diagram for the VL values illustrates that the visibility level is higher than the minimum value (5 in this case) in the range of distances where the criterion for visual comfort overrides the criterion for visual performance. In this range of distances, the road surface luminance decreases in an exponential manner – which is a straight line in the logarithmic diagram for the road surface luminance.

The profiles - supplemented with driving distance, driving time and comments - are also available as a large table in a sheet labelled “Table”.

7.6 An additional user part

There is an additional user part with input and results for a second driver. It shows the visibility levels for a second driver with a different driving speed and/or a different age compared to the first driver for which the profile of road surface luminance has been derived. An example of use is shown in figure 5.

5.a: 60 year driver at 110 km/h

Second driver speed	Second driver age	Second stopping distance	VL for second driver	
			reference position	interior zone
km/h	23-75 y	m		
110	60,0	230	3,79	4,98

5.b: 60 year driver at 100 km/h

Second driver speed	Second driver age	Second stopping distance	VL for second driver	
			reference position	interior zone
km/h	23-75 y	m		
100	60,0	190	5,22	6,89

5.c: 23 year driver at 110 km/h

Second driver speed	Second driver age	Second stopping distance	VL for second driver	
			reference position	interior zone
km/h	23-75 y	m		
110	23,0	230	5,10	6,10

Figure 5: Examples of input and results for a second driver.

The example concerns driving at 110 km/h with an associated stopping distance of 230 m (applies for Norway). A normal design results in an L_{th} value of 587 cd/m^2. This is judged to be too much and, therefore, the L_{th} value is reduced to 350 cd/m^2 by reducing the maximum road surface luminance to this value.

The result is a visibility level of 3,79 for a 60 year person driving at the full speed of 110 km/h; refer to figure 5.a.

This rather low visibility level may cause concern and, therefore, it is assumed that a 60 year person will reduce his speed to 100 km/h. This raises the visibility level to 5,22; refer to figure 5.b.

A 75 year person would have to reduce his speed to 95 km/h (not shown).

Additionally, it is assumed that a young person will drive at the full speed of 110 km/h. He will experience a visibility level of 5,22; refer to figure 5.c.

Because of this, it may be defendable to reduce the L_{th} value from 587 cd/m^2 to 350 cd/m^2.

8. Examples of calculations

Annex B presents some general examples of use of the excel file. There is a short introduction in B.1, while the examples themselves are given in B.2 and B.3.

In B.2, the examples relate to the influence of the criteria, which are the visibility level VL for visual performance, the t_{10} value for visual comfort and the optional criterion for the luminance L_{in} in the interior zone. None of these or other examples invoke the maximum luminance criterion.

In B.3 the examples relate to the influence of the level of daylight glare measured by the L_{seq} value at the drivers reference location, the influence of the driving speed and the influence of the age of the driver.

Annex C presents examples intended for comparison to recommendations in CIE 88:2004 and CIE 88:1990. Again, there is a short introduction in C.1, while the examples themselves are given in:

- C.2 Criterion for the initial luminance in the threshold zone of CIE 88:2004,
- C.3 Criterion for the initial luminance in the threshold zone of CIE 88:1990,
- C.4 The driving time in the transition zone,
- C.5 The luminance in the interior zone.

Some tentative conclusions are:

- The criterion for the initial luminance in the threshold zone L_{th} of CIE 88:2004 is incomplete, as it is based only on the perceived contrast of an object, but not taking the actual stopping distance into account,
- At least some agreement can be obtained with the k factor of CIE 88:1990,
- The driving time in the transition zone can be shorter than the 20 seconds of the luminance profile given in both CIE 88:1990 and CIE 88:2004 – perhaps up to 12 seconds depending on the level of daylight,
- Concerning the road surface luminance in the interior zone L_{in}, there is no convincing way to provide agreement between the excel file (provides levels comparable to road lighting) and the recommendations in CIE 88:1990 and CIE 88:2004 (provides higher levels),
- The excel file points to a stronger variation of the initial luminance in the threshold zone L_{th} with the stopping distance than reflected in CIE 88:2004 (no variation) and CIE 88:1990 (some variation of the k factors).

Annex A: Input and results

A.1 The user part of the excel file

A page "Input and results" of the excel file is shown in figure A.1. It has four parts with the main user part, an additional user part, a table linking stopping distances to driving speeds and a table with explanations.

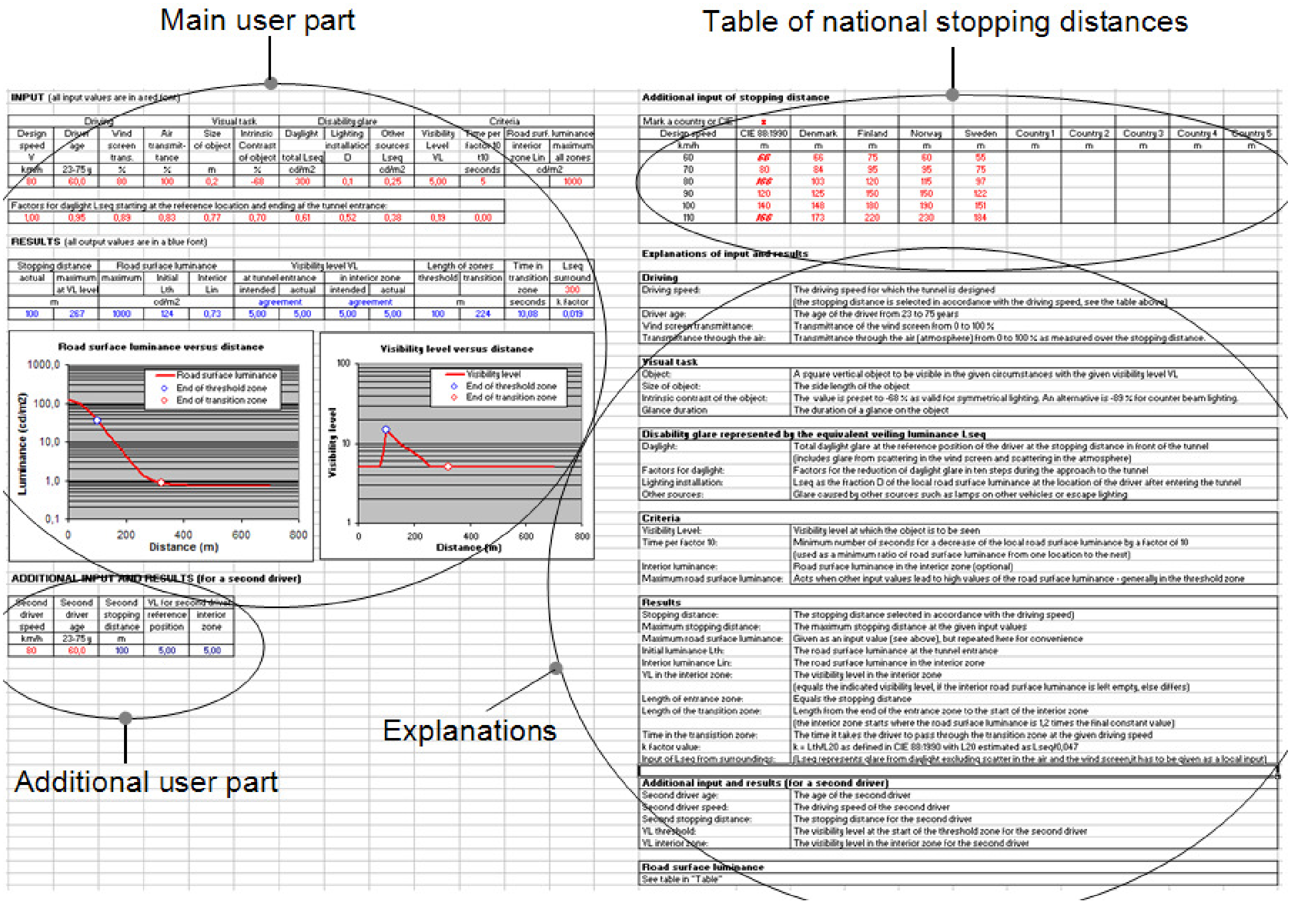


Figure A.1: The page "input and results".

In all cases, values in a red font are input values and values in a blue font are results. Some results are also shown in diagrams. Whenever input values are changed, the results and the diagrams change accordingly.

Input values, text and explanations can be changed, results must not be changed.

The table of national stopping distances is shown in figure A.2. It has rows for the driving speeds of 60, 70, 80, 90, 100 and 110 km/h and columns for countries. It is introduced for the reason that most countries define national stopping distances that are often different from country to country.

The table contains stopping distances for "CIE 88:1990". It is based on the values of 60, 100 and 160 m that are used in table 5.4 of CIE 88:1990 and shown in fat in figure A.2. These are assumed to apply for the driving speeds of 60, 80 and 110 km/h respectively. The other values are filled in by interpolation.

At present, only stopping distances for the Nordic countries of Denmark, Finland, Norway and Sweden have been inserted.

If a user wishes to use other stopping distances, he will have to insert the relevant values into one of the columns and change the label of the column accordingly.

A user also has to mark the column that he wishes to use by setting a mark above the column and deleting marks above other columns (if any). The mark can be anything different from blank.

Mark a country or CIE	x									
Design speed	CIE 88:1990	Denmark	Finland	Norway	Sweden	Country 1	Country 2	Country 3	Country 4	Country 5
km/h	m	m	m	m	m	m	m	m	m	m
60	***60***	66	75	60	55					
70	80	84	95	95	75					
80	***100***	103	120	115	97					
90	120	125	150	150	122					
100	140	148	180	190	151					
110	***160***	173	220	230	184					

Figure A.2: Table of national stopping distance with a mark for the relevant column.

The main user part has an input for the design speed, but a stopping distance is also needed. This stopping distance is selected from the marked column in the row that matches the driving speed.

In this way, the table provides the input of the stopping distance to the main user part. This applies also for the additional user part that has an input value of the driving speed of a second driver. There is no further discussion of the table.

The main user part is shown in figure A.3.

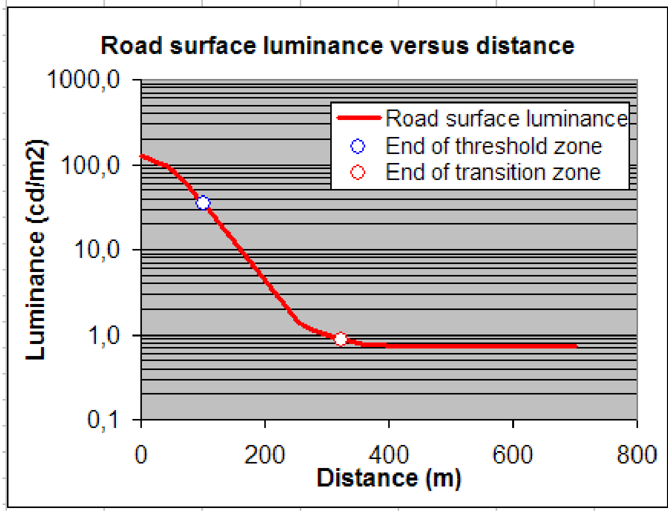
INPUT (all input values are in a red font)

Driving				Visual task		Disability glare			Criteria			
Design	Driver	Wind	Air	Size	Intrinsic	Daylight	Lighting	Other	Visibility	Time per	Road surf. luminance	
speed	age	screen	transmit-	of object	Contrast		installation	sources	Level	factor 10	interior	maximum
V		trans.	tance		of object	total Lseq	D	Lseq	VL	t10	zone Lin	all zones
km/h	23-75 y	%	%	m	%	cd/m2		cd/m2		seconds	cd/m2	
80	60,0	80	100	0,2	-68	300	0,1	0,25	5,00	5		1000

Factors for daylight Lseq starting at the reference location and ending af the tunnel entrance:										
1,00	0,95	0,89	0,83	0,77	0,70	0,61	0,52	0,38	0,19	0,00

RESULTS (all output values are in a blue font)

Stopping distance		Road surface luminance			Visibility level VL				Length of zones		Time in	Lseq
actual	maximum	maximum	Initial	Interior	at tunnel entrance		in interior zone		threshold	transition	transition	surround
	at VL level		Lth	Lin	intended	actual	intended	actual			zone	300
m		cd/m2			agreement		agreement		m		seconds	k factor
100	267	1000	124	0,73	5,00	5,00	5,00	5,00	100	224	10,08	0,019



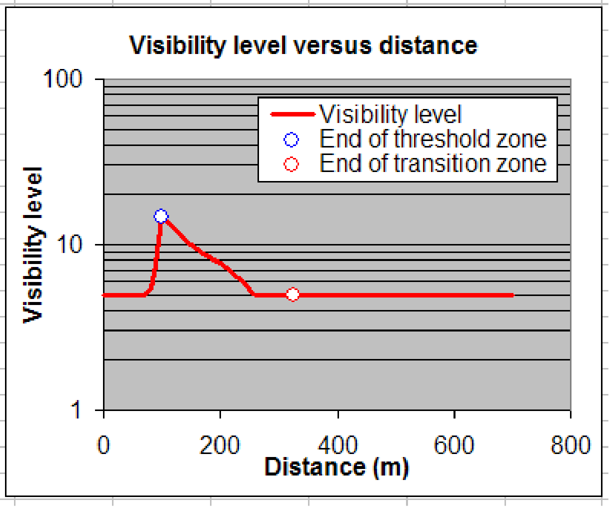


Figure A.3: The main user part.

The input and the results of the main user part are accounted for in some detail in A.2 to A.6.

The results of the main user part applies for a driver of a particular age and driving speed and may be considered to reflect a design of the tunnel lighting for this driver. The additional user part provides visibility levels for a second driver in the same conditions, but of a different age and/or driving speed. Refer to figure A.4.

Figure A.4: The additional user part.

Second driver speed	Second driver age	Second stopping distance	VL for second driver reference position	VL for second driver interior zone
km/h	23-75 y	m		
80	60,0	100	5,00	5,00

The two visibility levels for the second driver apply for respectively the reference position of the second driver and the interior zone. There is no further discussion of the additional user part.

The explanations are shown in figure A.5.

Driving	
Driving speed:	The driving speed for which the tunnel is designed
	(the stopping distance is selected in accordance with the driving speed, see the table above)
Driver age:	The age of the driver from 23 to 75 years
Wind screen transmittance:	Transmittance of the wind screen from 0 to 100 %
Transmittance through the air:	Transmittance through the air (atmosphere) from 0 to 100 % as measured over the stopping distance.
Visual task	
Object:	A square vertical object to be visible in the given circumstances with the given visibility level VL
Size of object:	The side length of the object
Intrinsic contrast of the object:	The value is preset to -68 % as valid for symmetrical lighting. An alternative is -89 % for counter beam lighting.
Exposure time (not shown)	The duration of a glance on the object, set to a fixed value of 0,5 seconds
Disability glare represented by the equivalent veiling luminance Lseq	
Daylight:	Total daylight glare at the reference position of the driver at the stopping distance in front of the tunnel
	(includes glare from scattering in the wind screen and scattering in the atmosphere)
Factors for daylight:	Factors for the reduction of daylight glare in ten steps during the approach to the tunnel
Lighting installation:	Lseq as the fraction D of the local road surface luminance at the location of the driver after entering the tunnel
Other sources:	Glare caused by other sources such as lamps on other vehicles or escape lighting
Criteria	
Visibility Level:	Visibility level at which the object is to be seen
Time per factor 10:	Minimum number of seconds for a decrease of the local road surface luminance by a factor of 10
	(used as a minimum ratio of road surface luminance from one location to the next)
Interior luminance:	Road surface luminance in the interior zone (optional)
Maximum road surface luminance:	Acts when other input values lead to high values of the road surface luminance - generally in the threshold zone
Results	
Stopping distance:	The stopping distance selected in accordance with the driving speed)
Maximum stopping distance:	The maximum stopping distance at the given input values
Maximum road surface luminance:	Given as an input value (see above), but repeated here for convenience
Initial luminance Lth:	The road surface luminance at the tunnel entrance
Interior luminance Lin:	The road surface luminance in the interior zone
VL in the interior zone:	The visibility level in the interior zone
	(equals the indicated visibility level, if the interior road surface luminance is left empty, else differs)
Length of entrance zone:	Equals the stopping distance
Length of the transition zone:	Length from the end of the entrance zone to the start of the interior zone
	(the interior zone starts where the road surface luminance is 1,2 times the final constant value)
Time in the transistion zone:	The time it takes the driver to pass through the transition zone at the given driving speed
k factor value:	k = Lth/L20 as defined in CIE 88:1990 with L20 estimated as Lseq/0,047
Input of Lseq from surroundings:	(Lseq represents glare from daylight excluding scatter in the air and the wind screen,it has to be given as a local i
Additional input and results (for a second driver)	
Second driver age:	The age of the second driver
Second driver speed:	The driving speed of the second driver
Second stopping distance:	The stopping distance for the second driver
VL threshold:	The visibility level at the start of the threshold zone for the second driver
VL interior zone:	The visibility level in the interior zone for the second driver
Road surface luminance	
See table in "Table"	

Figure A.5: Explanation of input and results.

Another page of the excel file labelled "Table" has a table with a stepwise account of the results. A part of this table with numerous rows is shown in figure A.6.

Step No.	Distance of object from the tunnel entrance	Driving time	Road surface luminance	Visibility level VL	Comments
	m	seconds	cd/m2		
1	0	0,00	455,30	5,00	Threshold zone; Lth
2	10	0,45	432,67	5,00	Threshold zone
3	20	0,90	405,56	5,00	Threshold zone
4	30	1,35	378,49	5,00	Threshold zone
5	40	1,80	351,46	5,00	Threshold zone
6	50	2,25	319,97	5,00	Threshold zone
7	60	2,70	279,55	5,00	Threshold zone
8	70	3,15	239,19	5,00	Threshold zone
9	80	3,60	194,42	5,26	Threshold zone
10	90	4,05	158,03	6,49	Threshold zone
11	100	4,50	128,45	7,75	End of threshold zone
12	110	4,95	104,41	7,28	Transition zone
13	120	5,40	84,87	6,88	Transition zone
14	130	5,85	68,98	6,50	Transition zone
15	140	6,30	56,07	6,12	Transition zone
16	150	6,75	45,58	5,74	Transition zone
17	160	7,20	37,05	5,41	Transition zone

Figure A.6: A part of the table in the page "Table".

A.2 Driving

The first group of input relates to driving and includes:

- the driving speed, either 60, 70, 80, 90, 100 or 110 km/h,
- the age of the driver,
- the transmittance of the wind screen,
- the transmittance of the air (atmosphere).

Driving				Visual task		Disability glare			Criteria			
Design speed V	Driver age	Wind screen trans.	Air transmit-tance	Size of object	Intrinsic Contrast of object	Daylight total Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Time per factor 10 t10	Road surf. luminance interior zone Lin	maximum all zones
km/h	23-75 y	%	%	m	%	cd/m2		cd/m2		seconds	cd/m2	
80	60,0	80	100	0,2	-68	300	0,1	0,25	5,00	5		1000

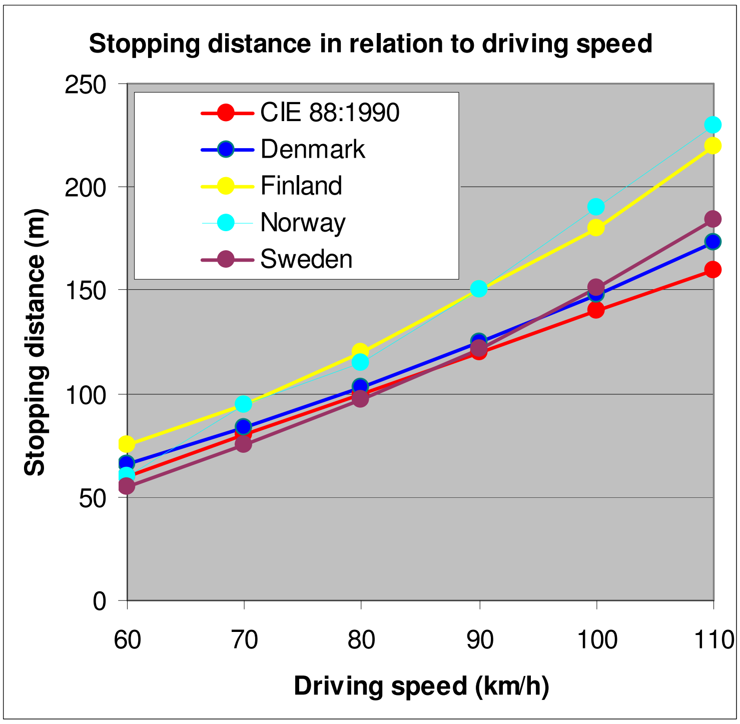
A.2.1 Driving speed

A driving speed is to be selected, either 60, 70, 80, 90, 100 or 110 km/h. For the selected driving speed, the excel file chooses the stopping distance in the table for national stopping distances as explained in A.1.

Additional input of stopping distance									
Mark a country or CIE	x								
Design speed	CIE 88:1990	Denmark	Finland	Norway	Sweden	Country 1	Country 2	Country 3	Country 4
km/h	m	m	m	m	m	m	m	m	m
60	***60***	66	75	60	55				
70	80	84	95	95	75				
80	***100***	103	120	115	97				
90	120	125	150	150	122				
100	140	148	180	190	151				
110	***160***	173	220	230	184				

Figure A.7 shows the stopping distance in relation to the driving speed for "CIE 88:1990" and the Nordic countries of Denmark, Finland, Norway and Sweden.

Figure A.7: Stopping distance in relation to driving speed.



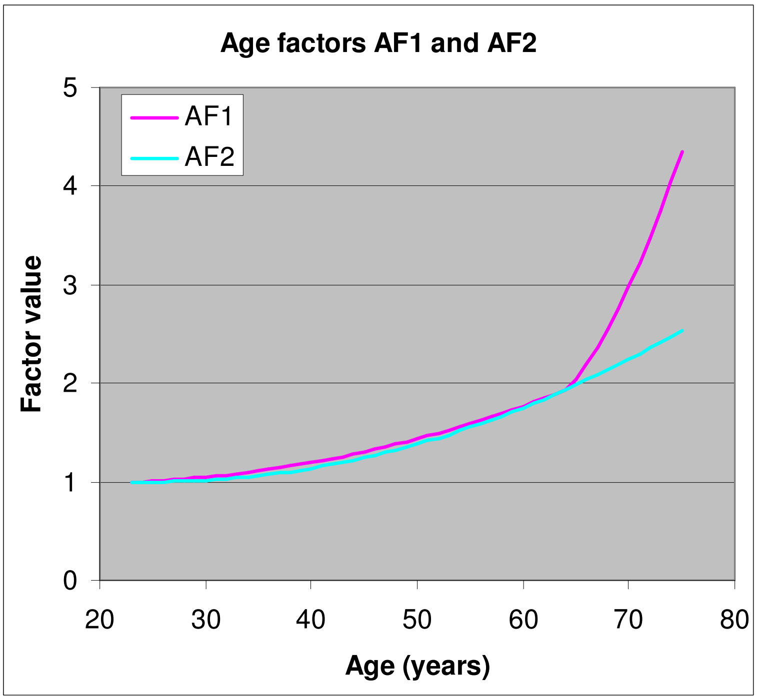
The driving speed has an influence on results only through the criterion for visual comfort, so that a higher driving speed in itself may lead to some prolongation of the transition zone.

The stopping distance, on the other hand, has a strong direct influence on the visibility of the object – for the reason that it has to be observed from the stopping distance. This also affects the whole luminance profile throughout the tunnel.

A.2.2 Age of the driver

The need for luminance increases with the age of the driver as indicated by an age factor AF1 shown in figure A.8. At the same time, L_{seq} values representing disability glare increase by an age factor AF2 also shown in figure A.8.

Figure A.8: Increase of the age factors AF1 and AF2 with age.



These factors are introduced in the manner that L_{seq} values are raised by multiplication with AF2, while all luminance values – both L_{seq} and road surface luminance values - are reduced by division with AF1.

Figure A.8 indicates that age has a strong influence. For the highest age of 75 years covered in the figure, the value of AF1 is 4,34, while the value of AF2 is 2,53.

The drivers age is preset to 60 years.

A.2.3 Absorption in the wind screen

Absorption in the wind screen, as described by a transmittance of maximum 100 %, makes the whole field of view appear darker to the driver. The effect is to raise the need for road surface luminance – in particular to raise the road surface luminance L_{in} in the interior zone.

The wind screen transmittance is preset to 80 %.

A.2.3 Absorption in the air

Absorption in the air is described by a transmittance of maximum 100 % as measured over a length of one stopping distance. Absorption in the air is assumed to reduce the apparent luminance of the object and of the road surface at the object – without any reduction of glare. This causes the need for an increase of the road surface luminance approximately in inverse proportion of the transmittance value. This applies in all the zones. The air transmittance is preset to 100 %.

A.3 The visual task

The second group of input relates to the visual task and includes:

- the size of the object,
- the intrinsic contrast of the object to the road surface forming the background,
- the exposure time of the object or glance duration (not available as an input value).

Driving				Visual task		Disability glare			Criteria			
Design speed V	Driver age	Wind screen trans.	Air transmit-tance	Size of object	Intrinsic Contrast of object	Daylight total Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Time per factor 10 t10	Road surf. luminance interior zone Lin	maximum all zones
km/h	23-75 y	%	%	m	%	cd/m2		cd/m2		seconds	cd/m2	
80	60,0	80	100	0,2	-68	300	0,1	0,25	5,00	5		1000

A.3.1 The size of the object

The size of the object is set to 0,2 m, which is the size of the reference obstacle introduced in CIE 88:2004.

The excel file replaces the square object with a circular object of the same area. In this case, the diameter is 0,226 m. The object size is then described by the diameter in minutes of arc as seen at the stopping distance.

A.3.2 The intrinsic contrast of the object

The intrinsic contrast of the object is the contrast formed by the actual luminance of the object and the luminance of the background road surface. The driver will see a reduced perceived contrast because of overlaying veiling luminance.

The intrinsic contrast of the object is preset to -68 % as valid for symmetrical lighting in accordance with CIE 88:2004. The alternative value is -89 % for counter beam lighting. However, it is permissible to set any value, positive or negative.

It is pointed out that counter beam lighting is normally used only for the entrance zone. Therefore, the contrast of -89 % can be used to determine the threshold luminance, but not the road surface luminance throughout the tunnel.

The above-mentioned values reflect assumptions in CIE 88:2004.

The intrinsic contrast of the object is defined as $C = L_{object}/L_{road\ surface} - 1$
where L_{object} is the luminance of the object,
and $L_{road\ surface}$ is the luminance of the road surface behind the object.

CIE 88:2004 assumes that the object has a diffuse reflection with a reflection factor ρ. This means that the L_{object} is given by $L_{object} = \rho \times E_v/\pi$.

Further, CIE 88:2004 introduces a contrast revealing coefficient q_C as the ratio between the luminance of the road surface $L_{road\ surface}$ and the vertical illuminance E_v at a specific location in the tunnel $q_C = L_{road\ surface}/E_v$. Accordingly, $L_{road\ surface} = q_C \times E_v$.

This leads to an expression for the intrinsic contrast: $C = L_{object}/L_{road\ surface} - 1 = (\rho \times E_v/\pi)/(q_C \times E_v) - 1 = \rho//(q_C \times \pi) - 1$

CIE 88:2004 sets ρ to 0,2 and introduces standardized values for q_C of 0,20 for symmetrical lighting and 0,6 for counter beam lighting. Inserting these values, C becomes -0,68 and -0,89 for respectively symmetrical and counter beam lighting.

The excel file does an initial calculation of the visibility level as if the contrast is positive. When the contrast is negative, the visibility level is divided by a "polarization factor" with a value less than 1. This value depends on the object size and the background luminance as illustrated in figure A.9.

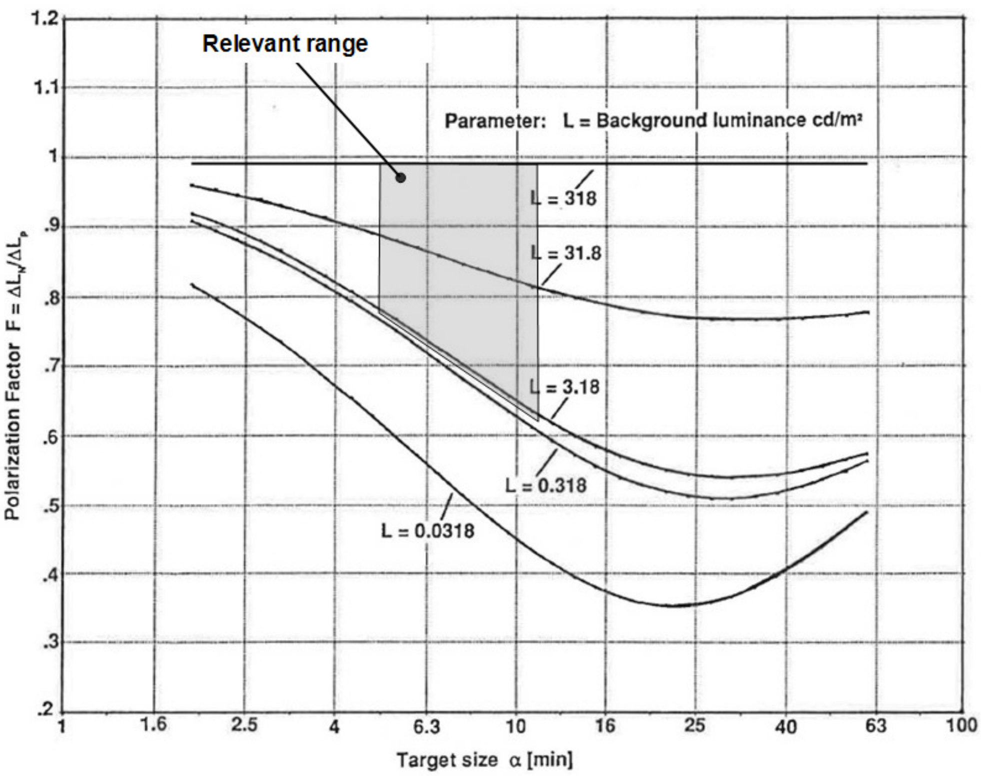


Figure A.9: The polarization factor as a function of the object size and the background luminance.

Figure A.9 is a copy of a diagram in the paper by Werner Adrian, to which the range relevant for tunnel lighting has been added. It can be seen that the factor is close to 1 for the high luminance levels that are relevant for the threshold zone, but significantly lower for the lower luminance levels relevant for the interior zone. Additionally, the lowest values are for large object sizes corresponding to low driving speeds.

As the visibility level is in inverse proportion to the value of this factor, negative contrast are more efficient to produce visibility than positive contrasts, and most efficient at low luminance levels and low driving speeds.

A.3.3 The exposure time

The exposure time represents the duration of a glance on the object. It is described by a factor to the visibility level. The factor has a value of 1 at 2 seconds, but increases with decreasing exposure time.

The value is preset to 0,5 second, which seems to be reasonable as a driver cannot spend a long time looking at an object in a scenery that may change fairly much in seconds. At this value, the effect is as if the visibility level is raised by 16 % with only a small variation from case to case.

A.4 Disability glare

The third group of input data relates to disability glare and includes:

- glare caused by daylight at locations of the driver in front of the tunnel entrance,
- the degree of glare caused by the lighting installation,
- additional glare caused by other glare sources.

Driving				Visual task		Disability glare			Criteria			
Design speed V	Driver age	Wind screen trans.	Air transmit-tance	Size of object	Intrinsic Contrast of object	Daylight total Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Time per factor 10 t10	Road surf. luminance interior zone Lin	maximum all zones
km/h	23-75 y	%	%	m	%	cd/m2		cd/m2		seconds	cd/m2	
80	60,0	80	100	0,2	-68	300	0,1	0,25	5,00	5		1000

A.4.1 Glare caused by daylight

Glare caused by daylight is indicated by a value of the equivalent veiling luminance L_{seq}, which applies for the reference location of the driver one stopping distance in front of the tunnel. In accordance with CIE 88:2004, there are three contributions to the total L_{seq} value:

a. from the surroundings,
b. from the air (atmosphere),
c. from the wind screen.

Concerning contribution a., a high value of for instance 300 cd/m^2 represents full daylight, while a low value represents weak daylight.

Concerning contributions b. and c., CIE 88:2004 recommends the L_{seq} values shown in table A.2.

Table A.2: CIE 88:2004 values for veiling luminance from the atmosphere and the wind screen.

Veiling levels	High	Medium	Low
Atmospheric veiling luminance (cd/m^2)	300	200	100
Windscreen veiling luminance (cd/m^2)	200	100	50

Together with L_{seq} comes a string of 11 fractions for the L_{seq} values. The first value is for the reference location while the last is for the location at the tunnel entrance. These values are respectively 1,00 and 0,00. The values in between represent a gradual decrease of glare during the approach to the tunnel entrance.

Factors for daylight Lseq starting at the reference location and ending af the tunnel entrance:										
1,00	0,95	0,89	0,83	0,77	0,70	0,61	0,52	0,38	0,19	0,00

These fractions reflect an average curve for both driving directions in a number of tunnels in Norway. It is pointed out that there are strong deviations from this curve in some of these tunnels. As an alternative, the values can be set to 1,00; 0,90; 0,80; 0,70; 0,60; 0,50; 0,40; 0,30; 0,20; 0,10 and 0,00 to reflect a linear decrease.

The fractions have been derived for the L_{seq} value for glare from the surroundings only. It is assumed that they apply for the total L_{seq} value as well.

A.4.2 The degree of glare

The degree of glare D applies for the glare caused by the luminaires of the tunnel lighting installation and is used to determine the L_{seq} value as D times the local road surface luminance at the location of the driver. Accordingly, this source of glare is applied only for locations of the driver inside of the tunnel, i.e. for the transition and interior zones.

Reasonable values of D can be evaluated by means of the maximum values of the threshold increment TI provided in EN 13201-2:2015 Road lighting - Part 2: Performance requirements. These values are 10 %, 15 % and 20 % for lighting classes with an average road surface luminance in the range from 2 down to 0,3 cd/m^2. As tunnels are mostly illuminated to a road surface luminance of 2 cd/m^2 or higher, the TI values of 5 %, 10 % and 15 % are assumed to be relevant for tunnel lighting.

TI is given by $TI = 65 \times L_{seq}/L^{0,8}$, where L is the road surface luminance. Accordingly, the degree of glare is found by $D = L_{seq}/L = TI/(65 \times L^{0,2})$. Such values are shown in figure A.10 in dependence of the road surface luminance and for the above-mentioned TI values.

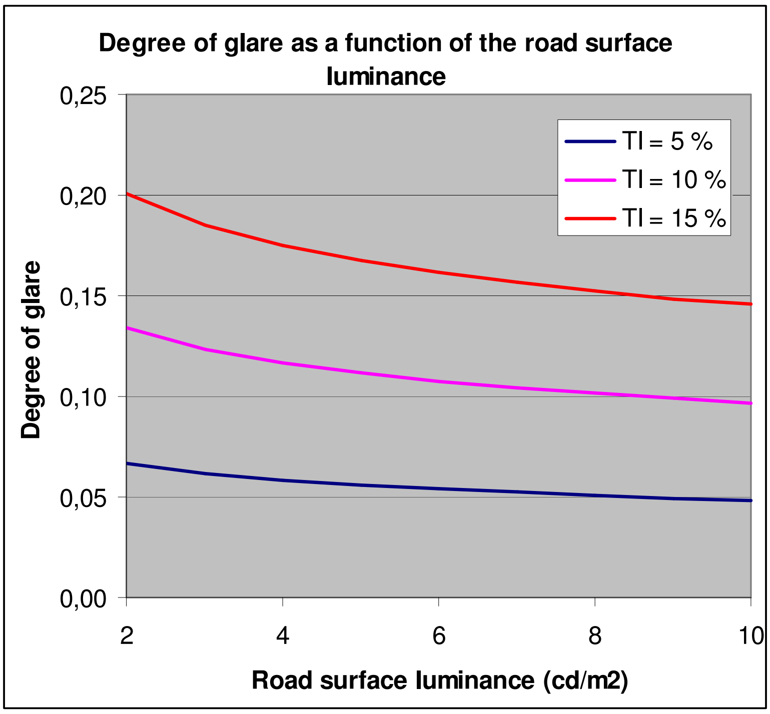


Figure A.10: Degree of glare as a function of the road surface luminance.

Judged from figure A.10, degrees of glare of 0,05, 0,10 and 0,15 seem to be relevant. It is noted that the concept of TI could have been used instead of the concept of D. However, the concept of D is preferred because the value of D stays constant when lighting installations are dimmed.

Note: The degree of glare D was actually used to describe disability glare in road lighting before the threshold increment TI was introduced.

A.4.3 Other glare sources

Other glare sources may for instance be emergency escape lights or delineator lights. However, the main aim is the glare caused by headlamps on oncoming vehicles in dual traffic tunnels. Some typical L_{seq} values are shown in table A.3, which has been copied from the report for COST action 331, Requirements for Horizontal Road Marking, European Communities 1999. The report can be downloaded from nmfv.dk.

The L_{seq} values of table A.3 apply for opposing vehicles on a straight road and for a luminous intensity of 200 cd for each of the two headlamps of a vehicle in the direction towards the driver. The L_{seq} values are virtually constant over a large range of distance to the opposing vehicles.

Table A.3: Values of L_{seq} (cd/m^2) for glare from headlamps of oncoming vehicles.

Number of oncoming vehicles	Lateral separation to oncoming vehicles			
	3,5 m	7,0 m	10,5 m	14,0 m
1	0,098	0,024	0,011	0,006
2	0,196	0,049	0,022	0,012
3	0,294	0,073	0,033	0,018
4	0,392	0,098	0,044	0,024
5	0,490	0,122	0,054	0,031

This L_{seq} value is preset to 0,25 cd/m^2.

A.5 Input data for criteria

The last group of input data relates to the criteria for the road surface luminance and includes:

- a minimum value of the visibility level VL,
- the maximum rate at which the road surface luminance can decrease, measured in seconds for a decrease of the luminance by a factor 10, t_{10},
- an optional value of the road surface luminance L_{in} in the interior zone,
- a maximum value of the road surface luminance in all zones.

.

Driving				Visual task		Disability glare			Criteria			
Design speed V	Driver age	Wind screen trans.	Air transmit-tance	Size of object	Intrinsic Contrast of object	Daylight total Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Time per factor 10 t10	Road surf. luminance interior zone Lin	maximum all zones
km/h	23-75 y	%	%	m	%	cd/m2		cd/m2		seconds	cd/m2	
80	60,0	80	100	0,2	-68	300	0,1	0,25	5,00	5		1000

A.5.1 The minimum visibility level VL

VL is the visibility level describing the visibility of the object. The minimum value for detecting the object is 1, but in practice the value should be higher to ensure that a driver can detect objects in real situations. The value of VL has been preset to 5.

The VL value has a strong influence on the level of road surface luminance.

A.5.2 The minimum time for a decrease of the road surface luminance t_{10}

The last criterion concerns visual comfort and is the minimum time measured in seconds for a decrease of the luminance by a factor 10, t_{10}. The preset value of 5 seconds seems to be relevant, but higher values could be considered. This criterion has an influence on the road surface luminance in the threshold and transition zones only.

A.5.3 The road surface luminance in the interior zone L_{in}

L_{in} is the luminance in the interior zone. If the input field is left blank, the above-mentioned VL criterion is applied in all the zones. If filled in, the excel file internally derives a new value of VL that makes the road surface luminance in the interior zone equal to the input value. This VL value is applied in the transition zone as well as in the interior zone.

This criterion has been introduced as an acceptance that the L_{in} value is in practice often set on the basis of other criteria than just visibility.

A.5.4 The maximum road surface luminance

Whenever input values and other criteria demand a local road surface luminance above the maximum, this criterion acts to replace the luminance value by he maximum value.

This is tested throughout all the zones, but actions of this criterion – if any – can be expected to be at locations at the start of the threshold zone only. This criterion has an effect not only at the particular locations, but may also have an effect at the following locations in the threshold and transition zones by means of the criterion for visual comfort.

This criterion has been introduced in order the define the highest acceptable luminance in the threshold zone. The value is preset to 1000 cd/m^2, but should probably be set lower in some cases.

The criterion has the side effect that the iteration used for the calculation of the road surface luminance profile always converges smoothly. This side effect is lost, if the maximum value is set very high. Therefore, the value should not exceed 3000 cd/m^2.

A.6 Results of calculations

A.6.1 Introduction

The final result is the profile of the road surface luminance. To this is added a profile of VL values. These profiles are shown in diagrams, refer to figure A.3.

Additional results are:

a. the actual stopping distance for the relevant driving speed,
b. the maximum stopping distance,
c. the maximum road surface luminance (a repetition of the maximum road surface luminance set by the criterion),
d. the luminance at the tunnel entrance in the threshold zone L_{th},
e. the luminance in the interior zone L_{in},

f. the intended VL value,
g. the actual VL value for the reference location of the driver with the object placed at the tunnel entrance,
h. the intended VL value in the interior zone (deviates from the minimum VL value, when an L_{in} value has been set),
i. the actual VL value in the interior zone,
j. the length of the threshold zone (equal to the stopping distance),
k. the length of the transition zone (starts at the end of the threshold zone and ends where the luminance is 1,2 times the luminance in the interior zone),
l. the duration of driving in the transition zone,
m. the k factor (based on an estimated value of L_{20}).

Stopping distance		Road surface luminance			Visibility level VL				Length of zones		Time in	Lseq
actual	maximum	maximum	Initial	Interior	at tunnel entrance		in interior zone		threshold	transition	transition	surround
	at VL level		Lth	Lin	intended	actual	intended	actual			zone	300
m		cd/m2			agreement		agreement		m		seconds	k factor
100	267	1000	124	0,73	5,00	5,00	5,00	5,00	100	224	10,08	0,019

The results fall into a number of groups that are considered in the sub sections below.

A.6.2 Stopping distance

The actual stopping distance is intended to provide an overview and verification that the proper stopping distance has been selected by the excel file.

The maximum stopping distance is the stopping distance that can be achieved in view of the VL value and other input values without invoking the criterion for the maximum road surface luminance.

Therefore, if the actual stopping distance exceeds the maximum, the criterion will act to reduce the road surface luminance in parts of the threshold zone to the maximum value. This results in a reduction of the visibility level in those parts of the threshold zone.

A.6.3 Road surface luminance

The maximum for the road surface luminance is shown as a reminder of this limitation.

The initial luminance L_{th} is the road surface luminance at the tunnel entrance, while the interior luminance L_{in} is the road surface luminance in the interior zone. L_{in} is either a calculated value, or the value set optionally as a criterion. Refer to A.5.3.

A.6.4 Visibility level VL

The visibility level VL at the tunnel entrance applies for the driver at the reference location. The intended and the actual values are both provided in order to verify that they agree, which is also stated by "agreement".

However, when the criterion for maximum road surface luminance is invoked because of a long stopping distance, refer to A.6.2, the actual visibility level becomes smaller than the intended value and the statement is changes to "disagreement". This does not necessarily mean that the result is useless – it is sometimes necessary to deal with long stopping distance and the loss in visibility level may be acceptable.

The visibility level VL in the interior zone is either the value set as a criterion, or a value that provides the L_{in} value set optionally as a criterion. Refer to A.5.3.

The intended and the actual value are both provided. The result should generally be "agreement".

A.6.5 Comparison to CIE 88:1990 and CIE 88:2004

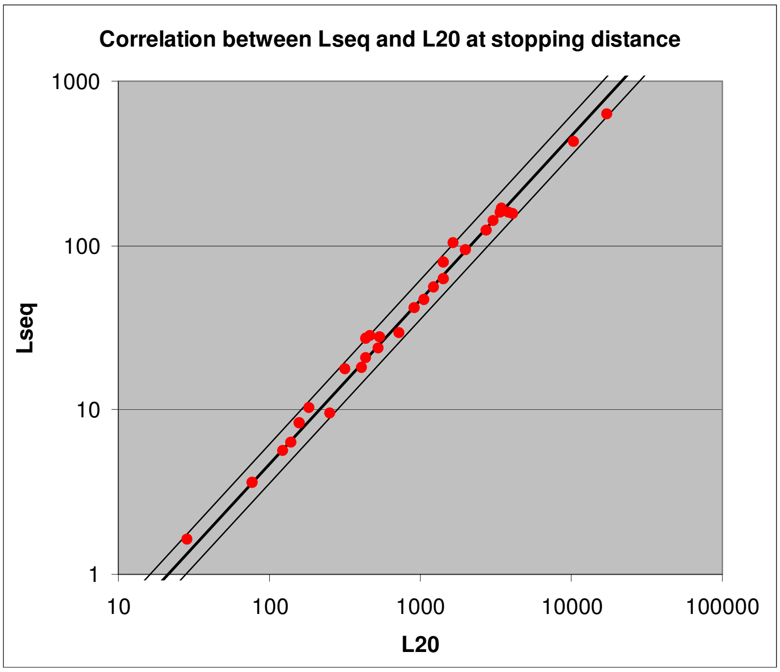
The last four results have been added for easy comparison to CIE 88:1990 and CIE 88:2004.

Only the k factor needs to be explained. It is defined in CIE 88:1990 as the ratio between the L_{th} value and an L_{20} value. The L_{20} value is also defined in CIE 88:1990.

This means that it is necessary to determine the L_{20} value before the k factor can be determined. This is done by means of a correlation between values of and L_{seq} and L_{20} as derived for 15 tunnels in Norway measured in both directions. This correlation is shown figure A.11, which also shows a regression line representing a ratio of 0,047. Accordingly, L_{20} is estimated by $L_{20} = L_{seq}/0{,}047$.

However, it is assumed that L_{20} only takes the surroundings to the tunnel into account, not the disability glare caused by scattering in the air and in the wind screen of the vehicle. Therefore, the L_{seq} value used to derive the L_{20} value should include the L_{seq} value of the surroundings only. Accordingly, this L_{seq} value has to be supplied as an additional input value.

Figure A.11: Correlation between of L_{seq} and L_{20} for 15 tunnels in Norway measured in both directions.



Note: The thin lines in figure A.12 represent twice a standard deviation of 15 %.

Annex B: General examples of calculations

B.1 Introduction

This annex accounts for some general results of use of the excel file by means of examples.

The starting point for these examples is the preset input data shown in figure A.3. Changes are made clear in each case.

The examples in B.2 show the influence of the criteria, which are the visibility level VL for visual performance, the t_{10} value for visual comfort and the optional criterion for the luminance L_{in} in the interior zone.

The examples in B.3 show the influence of the level of daylight glare measured by the L_{seq} value at the drivers reference location, the influence of the driving speed and the influence of the age of the driver.

B.2 Influence of the criteria

B.2.1 Visual performance

The criterion for visual performance is the minimum visibility level VL.

Figure B.1 shows the luminance profiles for of VL values of 3, 5 and 7 calculated for a driving speed of 80 km/h and an associated stopping distance of 100 m. The marks on the profiles indicate the ends of the threshold and transition zones.

It is seen that the VL value has a strong influence on the initial luminance L_{th} and the luminance L_{in} in the interior zone, and a weak influence on the length of the transition zone. Similar results are obtained for other driving speeds.

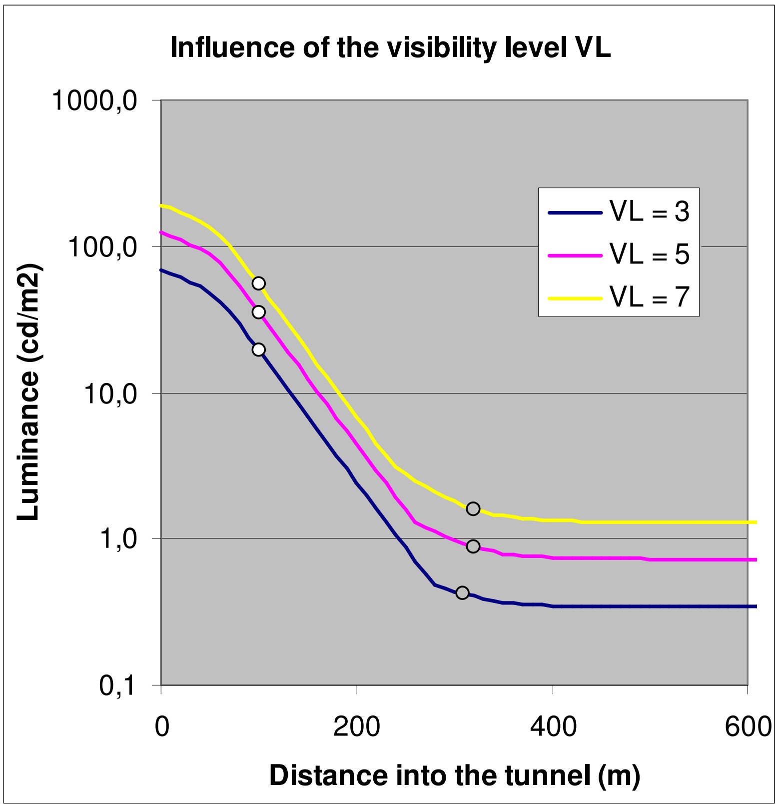


Figure B.1 Luminance profiles for different values of the visibility level VL.

B.2.2 Visual comfort

The criterion for visual comfort is the minimum time in seconds in which the luminance can decrease by a factor of 10, t_{10}.

Figure B.2 shows the luminance profiles for values of t_{10} of 0, 5 and 10 seconds calculated for a driving speed of 80 km/h and an associated stopping distance of 100 m. The marks on the profiles indicate the ends of the threshold and transition zones.

For a value of t_{10} of 0 seconds, there is no influence of this criterion, so that the criterion for visual performance acts alone. This profile has an initial bell shape, which covers the threshold zone, and is repeated like echoes a number of times in the transition zone, until the constant level in the interior zone is reached.

For a value of t_{10} of 5 seconds, the profile becomes more smooth, but with little overall change. This shows that the criterion has prevented the rapid decreases of the bell shapes.

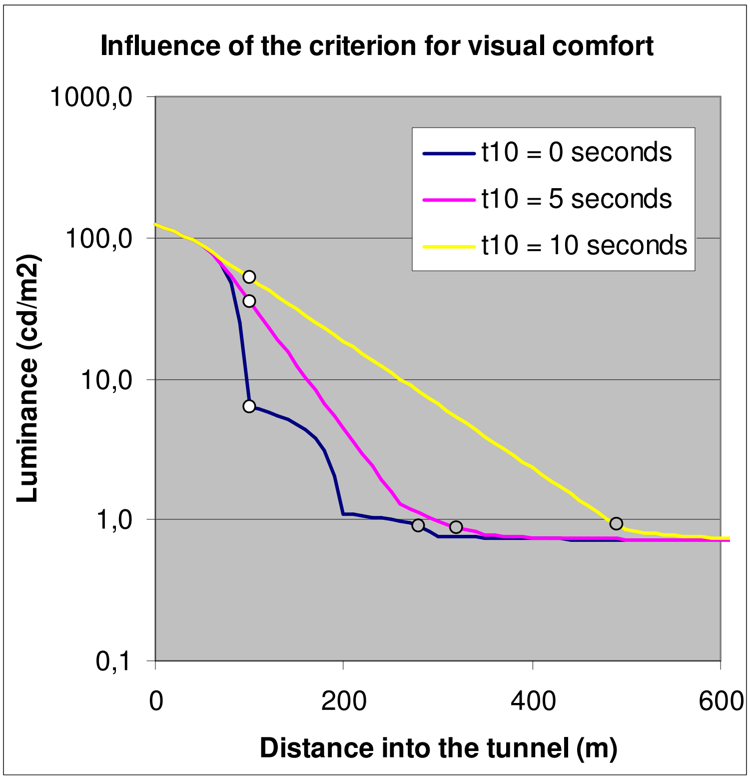
For a value of t_{10} of 10 seconds, the luminance profile is forced to become wider by the criterion. This leads to a prolongation of the transition zone.

The criterion does not affect the luminance L_{in} in the interior zone.

Luminance profiles for other driving speeds are similar to those shown in figure B.2 with, however, a somewhat stronger effect of the criterion for lower speeds and a somewhat weaker effect at higher speeds.

This shows that the criterion for visual comfort prevents steep slopes of the luminance profiles both locally and overall to a degree depending on the input value and the driving speed. It is assumed that a value of t_{10} of 5 seconds is adequate.

Figure B.2: Luminance profiles for different t_{10} values.



B.2.3 Luminance in the interior zone

When a particular value of the luminance in the interior zone L_{in} is desired, the value is inserted in the relevant field. Else the field is left empty, meaning that this criterion is not applied.

Figure B.3 shows luminance profiles for values of L_{in} left empty or set to 2 or 3 cd/m^2, and calculated for a driving speed of 80 km/h and an associated stopping distance of 100 m. The marks on the profiles indicate the ends of the threshold and transition zones.

It is seen that the luminance profiles comply with the settings of L_{in}.

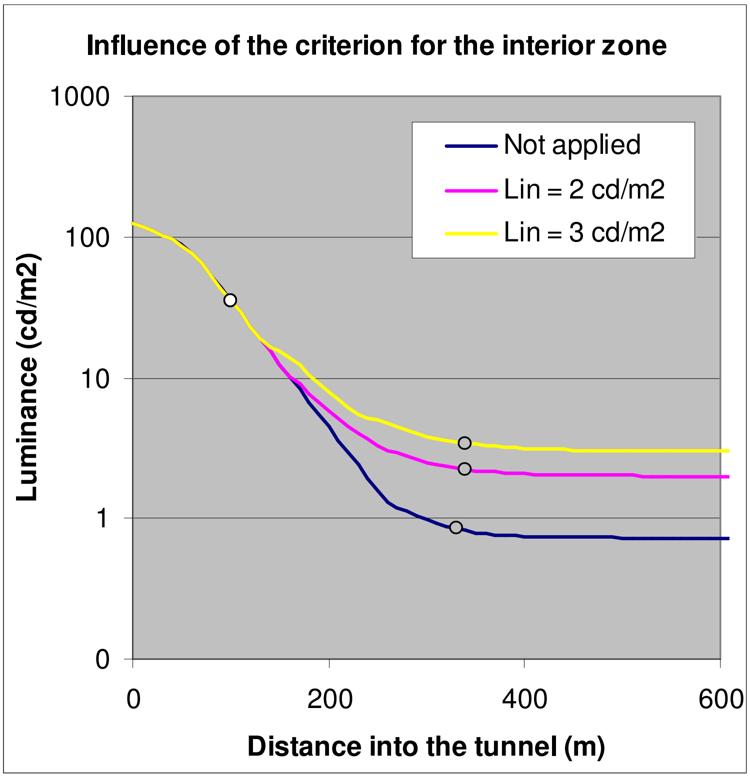


Figure B.3: Luminance profiles for different settings of L_{in}.

B.3 Influence of the daylight level, the driving speed and the drivers age

B.3.1 Influence of the daylight level

Daylight is represented by a value of L_{seq} for the reference position of the driver and a set of fractions for positions closer to the tunnel entrance.

Figure B.4 shows luminance profiles for values of L_{seq} of 30, 100 and 300 cd/m^2 calculated for a driving speed of 80 km/h and an associated stopping distance of 100 m. The marks on the profiles indicate the ends of the threshold and transition zones.

It is seen that the L_{seq} value has a strong influence on the initial luminance in the threshold zone – roughly in a linear scale - and some influence on the length of the transition zone.

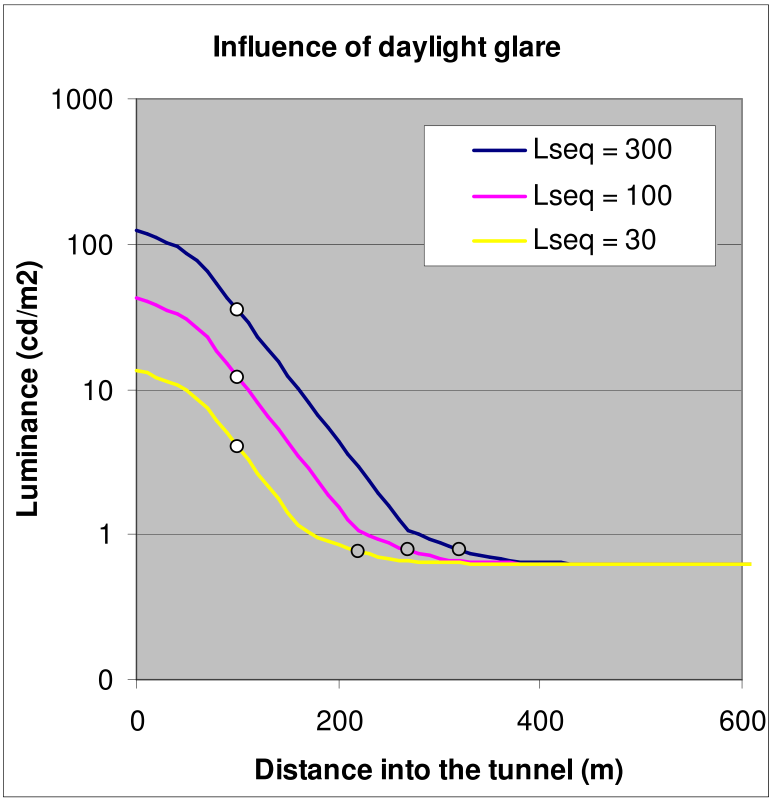


Figure B.4: Luminance profiles for different settings of L_{seq}.

B.3.2 Influence of the driving speed and the stopping distance

Figure B.5 shows luminance profiles for driving speeds of 60, 80 and 110 km/h with associated stopping distances of respectively 60, 100 and 160 m. The marks on the profiles indicate the ends of the threshold and transition zones.

It is seen that the driving speed has a strong influence on the initial luminance in the threshold zone L_{th}, the length of the transition zone and the luminance in the interior zone L_{in}. It is actually the stopping distances associated with the driving speeds, not the driving speeds themselves, which have this strong influence on the results. Accordingly, figure B.5 can be understood as providing the influence of stopping distances of 60, 100 and 160 m.

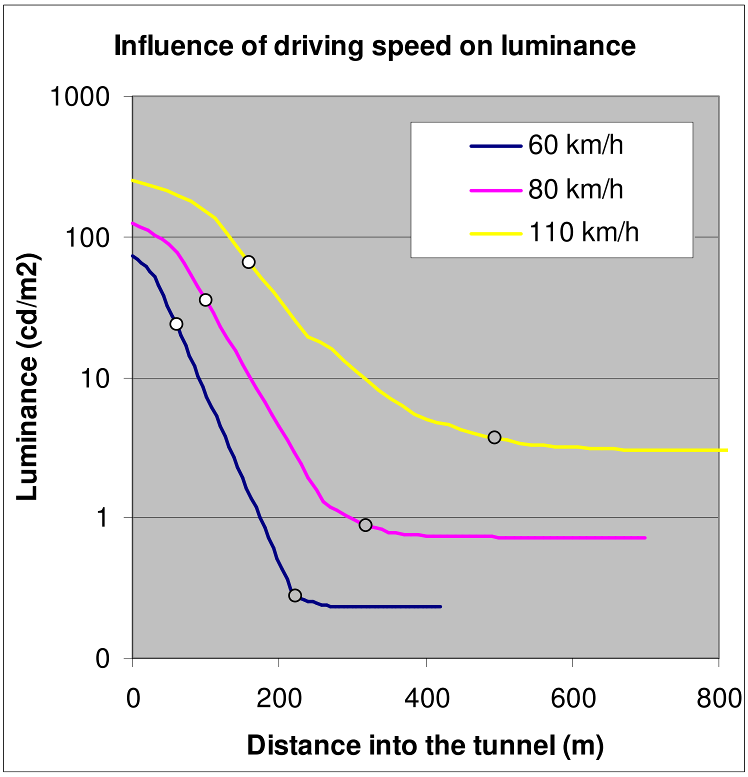


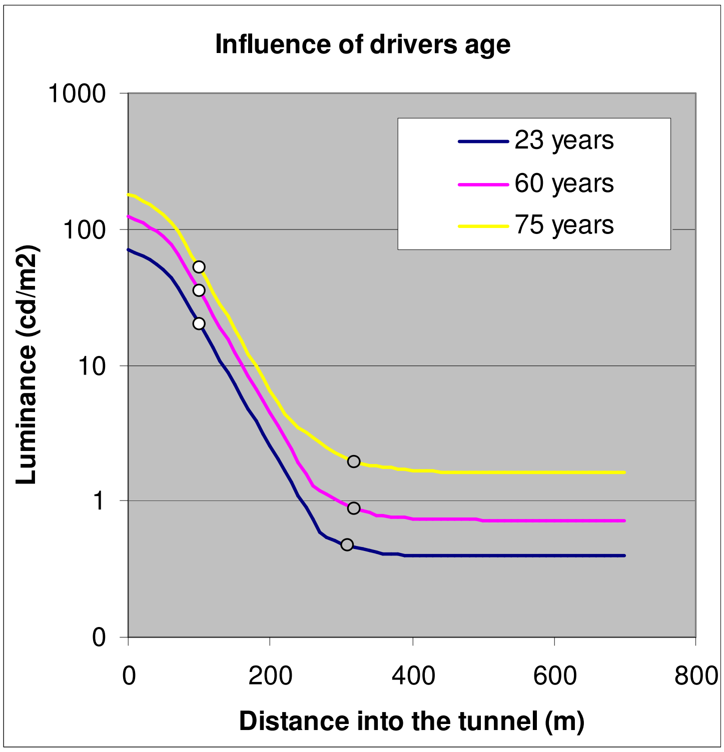
Figure B.5: Luminance profiles for different settings of the driving speed.

B.3.3 Influence of the drivers age

Figure B.6 shows luminance profiles for drivers age of 23, 60 and 75 years calculated for a driving speed of 80 km/h and an associated stopping distance of 100 m. The marks on the profiles indicate the ends of the threshold and transition zones.

It is seen that the drivers age has a strong influence on the luminance profiles, and in particular on the luminance in the interior zone L_{in}. There is no influence on the length of the transition zone

Figure B.6: Luminance profiles for different ages of the driver.



Annex C: Examples of comparison to recommendations in CIE 88:2004 and CIE 88:1990

C.1 Introduction

This annex accounts for comparison to recommendations in CIE 88:2004 and CIE 88:1990 by means of examples.

As in annex B, the starting point for these examples is the preset input data shown in figure A.3. Changes are made clear in each case.

The examples in C.2 and C.3 relate to the criteria or the initial luminance in the threshold zone of CIE 88:2004 and CIE 88:1990.

The examples in C.4 relate to the driving in the transition zone and those in C.5 to the road surface luminance in the interior zone.

C.2 Criterion for the initial luminance in the threshold zone of CIE 88:2004

CIE 88:2004 offers the criterion for the initial luminance in the threshold zone L_{th} that the perceived contrast of an object is minimum -28 %.

CIE 88:2004 also provides methods for the calculation of the minimum perceived contrast, in particular that the object has a diffuse reflection with a reflectance of 0,2 and that the contrast revealing factor has certain values for symmetrical lighting and counter beam lighting. This results in intrinsic contrast values of the object of -68 % and -89 % for the two lighting systems respectively.

Further, CIE 88:2004 states that the size of the object is 20 cm times 20 cm. However, the size itself is not used in the calculation of the perceived contrast.

For comparison, the perceived contrast values calculated with the excel file as a function of the stopping distance are shown in figure C.1. The criterion of CIE 88:2004 of -28 % is also indicated.

NOTE: The excel file does not have an output result for the perceived contrast, but the value can easily be calculated as the intrinsic contrast given as an input value multiplied by $L_{th}/(L_{th} + L_{seq})$.

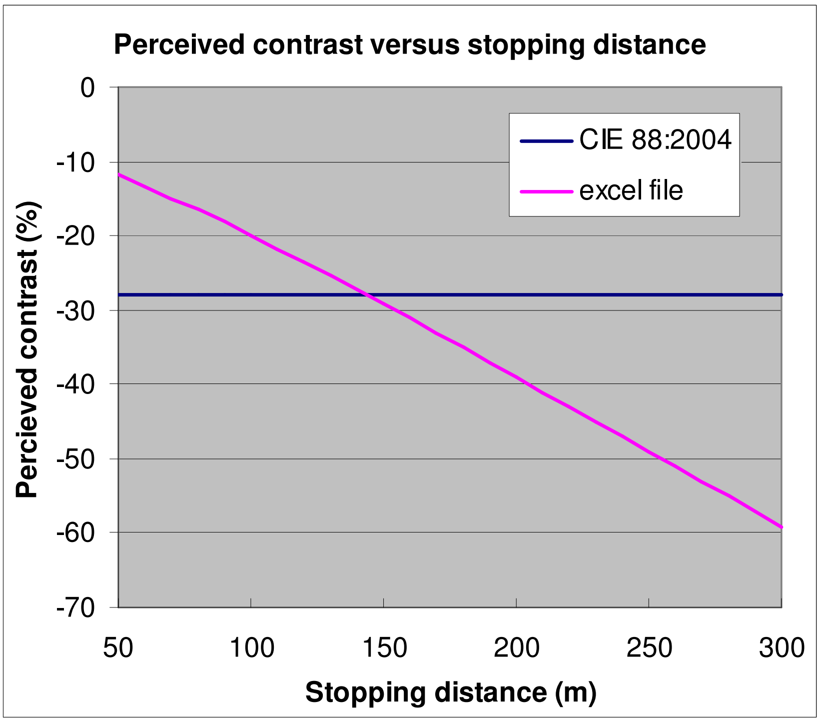


Figure C.1: Perceived contrast versus stopping distance.

Figure C.1 shows that the calculated perceived contrast is not constant, but decreases towards lower negative values with increasing stopping distance. This is natural, as the main factors for visibility are the perceived contrast and the apparent size of the object as seen from the stopping distance. The apparent size of the object decreases with increasing stopping distance and, therefore, it is necessary to compensate with a numerically larger perceived contrast.

Accordingly, the criterion of CIE 88:2004 is incomplete. It fits only at one particular stopping distance, and not at other stopping distances. This is probably a reason that the criterion of CIE 88:2004 has not been implemented in national standards/regulations in some countries.

C.3 Criterion for the initial luminance in the threshold zone of CIE 88:1990

CIE 88:1990 has the recommendations for the initial luminance in the threshold zone L_{th} given by the k factor values shown in figure C.2.

Figure C.2: CIE 88:1990 recommendations for the initial luminance in the threshold zone.

	Symmetrical lighting system ($L/E_V \leq 0,2$)	Counter Beam Lighting system ($L/E_V \geq 0,6$)
stopping distance	$k = L_{th}/L_{20}$	$k = L_{th}/L_{20}$
60m	0,05	0,04
100m	0,06	0,05
160m	0,10	0,07

The k factor is the ratio between L_{th} and the L_{20} value also defined in CIE 88:1990. Accordingly, the L_{th} value is obtained by $L_{th} = k \times L_{20}$.

In A.6 it is shown that the L_{20} value to some approximation is given by $L_{20} = L_{seq}/0{,}047$, where L_{seq} is the ceiling luminance caused by the surroundings to the tunnel opening (not including veiling luminance by scattering in the air nor in the wind screen of the vehicle). Accordingly, the L_{th} value can be obtained by $L_{th} = (k/0{,}047) \times L_{seq}$.

As the k factor values of figure C.2 are rather close to 0,047, the recommendations are really that the L_{th} should have about the same value as the L_{seq} with, however, some variation depending on the stopping distance and the lighting system.

This is reasonable, and demonstrates that the L_{th} value is selected in view of glare represented by the L_{seq} value.

However, calculations with the excel file leads to smaller k values than indicated in figure C.2, when taking only glare from the surroundings into account. The reason may be that the k values have been increased –

based on practical experience – in order to take additional glare from the above-mentioned sources into account or just to provide additional visibility.

If assuming that the total Lseq value is twice the L_{seq} value for the surroundings only, the excel file gives the values in table C.1.

Table C.1: Calculated k factors.

Stopping distance	Symmetrical lighting system (q_C = 0,2)	Counter beam lighting system (q_C = 0,6)
	$k = L_{th}/L_{20}$	$k = L_{th}/L_{20}$
60 m	0,022	0,018
100 m	0,040	0,028
160 m	0,080	0,054

The values of table C.1 are still smaller than those of figure C.2, but not to an unreasonable degree. A change of other input values – for instance increasing the age of the driver from 60 to 75 years, would bring better agreement. At least, some sort of agreement has been established.

However, one matter remains, that the calculated k factors vary with the stopping distance by a factor of three, while the k factors of CIE 88:1990 vary by a factor of two only. This shows that the stopping distance has a stronger influence than indicated by the k factors of CIE 88:1990.

C.4 The driving time in the transition zone

CIE 88:1990 and CIE 88:2004 both define a luminance profile in the transition zone that involves a driving time of 20 seconds. For comparison, figure C.3 shows the driving time in the transition zone - obtained with the excel file - as a function of the driving speed for a number of settings of the total L_{seq} value.

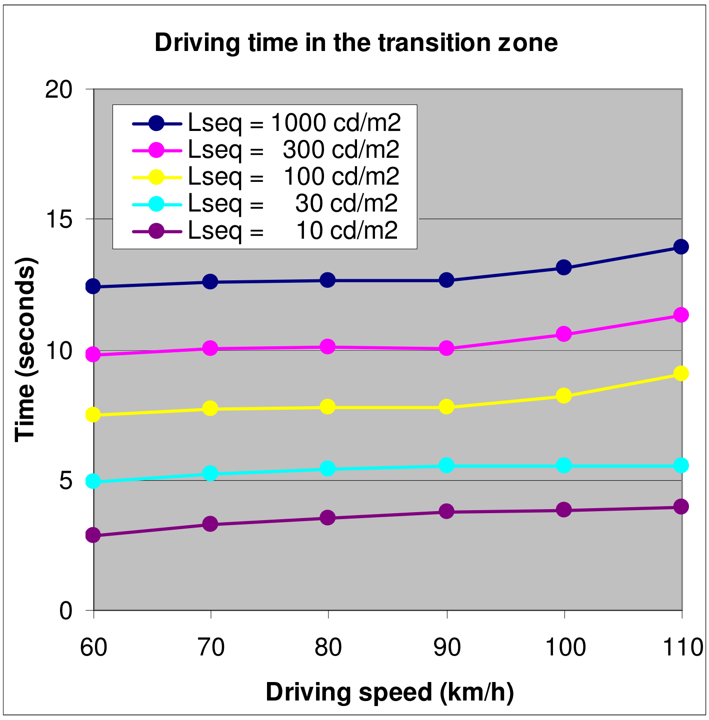


Figure C.3: Time in the transition zone for some settings of the total L_{seq} value.

Figure C.4 does indicate that the driving time is indeed almost independent on the driving speed, which is in agreement with CIE 88:1990 and CIE 88:2004.

However, figure C.4 does show that the driving time hardly reaches higher than 12 seconds for total L_{seq} values up to 500 or 600 cd/m^2. If this is accepted, it should be possible to use shorter transition zones.

Furthermore, figure C.4 does show that the driving time depends on the level of the total L_{seq} value. Therefore, it should be possible to use even shorter transition zones in conditions of weak daylight.

C.4.2 The luminance in the interior zone

CIE 88:1990 and CIE 88:2004 both give recommendations for the luminance in the interior zone L_{in}. These recommendations are shown in figures C.4 and C.5.

Interior zone average road surface luminance cd/m^2			
stopping Distance S.D.	Traffic flow: Low ≤ 100 vehicles/h	Traffic flow: Medium > 100 vehicles/h < 1 000 vehicles/h	Traffic flow: Heavy ≥ 1 000 vehicles/h
160 m	5	10	15
100 m	2	4	6
60 m	1	2	3

Figure C.4: CIE 88:1990 recommendations for the luminance in the interior zone.

Stopping Distance (m)	LONG TUNNELS Traffic flow [vehicles/hour/lane]	
	Low	Heavy
160 m	6	10
60 m	3	6

Stopping Distance (m)	VERY LONG TUNNELS Traffic flow [vehicles/hour/lane]	
	Low	Heavy
160 m	2,5	4,5
60 m	1	2

Figure C.5: CIE 88:2004 recommendations for the luminance in the interior zone.

The excel file produces road surface luminance values in the range of 0,25 to 3,0 cd/m^2 for driving speeds from 60 to 110 km/h. This is comparable to the range of 0,3 to 2,0 cd/m^2 as in the M classes of EN 13201-2:2015 “Road lighting - Part 2: Performance requirements” for road lighting, but much lower than the recommendations in figures C.4 and C.5.

The values of the excel file can of course be modified by changes of the input values, for instance by a change of the drivers age from 60 to 75 years, or by assumptions of more glare from the lighting installations. However, there is no convincing way to provide agreement with figures C.4 and C.5.

Because of the high levels of recommended road surface luminance values in the interior zone of tunnels, there must be some particular concerns that are relevant for tunnel lighting – but not for road lighting.