Analysis of tunnel lighting based on visual performance and visual comfort

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Foreword

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 and visual comfort. An additional criterion is an optional setting of the road surface luminance in the interior zone.

This tool is an excel file by the name "Analysis of tunnel lighting based on visual performance and visual comfort", which is freely available.

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

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.

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 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 circumstances indicated in the input and in view of criteria for visual performance, visual comfort and an optional setting of the luminance in the interior zone.

Once the drive is completed, a profile of the road surface luminance has been determined, starting at the tunnel entrance and passing through the threshold and transition zones well into the interior zone. This profile is based on an estimate generated by the excel file and is not correct. Therefore, the drive is repeated, resulting in a profile that is adjusted compared to the first profile. After a number of further drives, the correct profile has been established in an iterative procedure. The total number of drives is 20.

The calculations are the same all through the drive. However, the glare from daylight applies only for the threshold zone, which makes this zone special. There is no such clear distinction between the transition zone and the interior zone, where the road surface luminance decreases gradually towards a constant value L_{in}. In practice, however, it is useful 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 $1,2\times L_{in}$.

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

The adjustments of the profiles of the road surface luminance are based on the criteria discussed in sections 3, 4 and 5. An example of the profiles is 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 iterative procedure converges quickly.

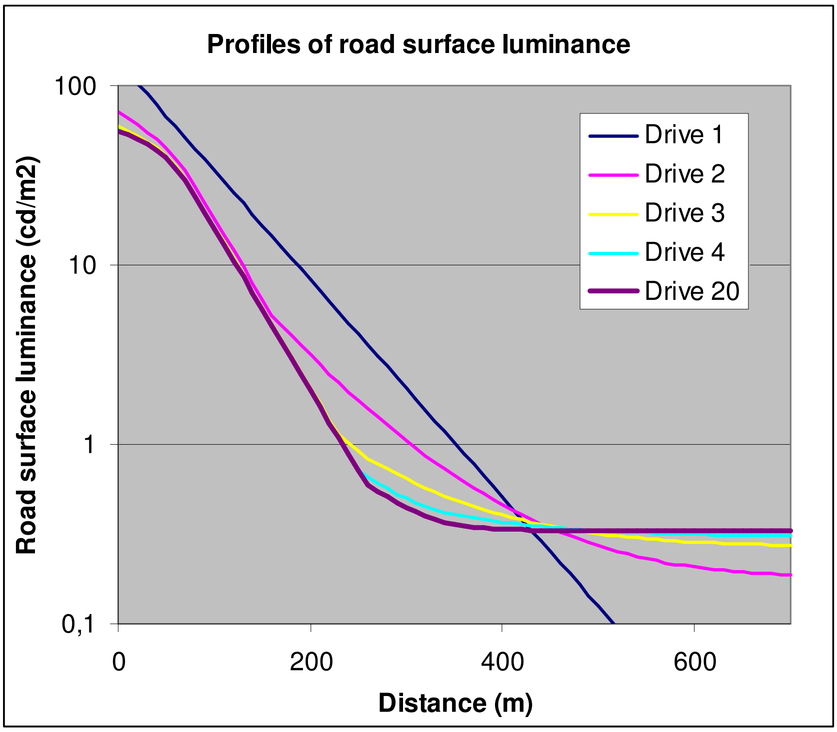


Figure 1: Example of profiles of road surface luminance in repeated drives.

However, the input values can define cases where the object cannot be made visible at the required visibility level. If so, the iterative procedure does not converge, but creates higher and higher luminance levels in each repetition of the drive. With the current preset input values, this happens when the stopping distance is longer than 320 m.

The final very high luminance level provides in itself a warning that the combination of input values is not feasible. As explained in section 6 on the results provided by the excel file, there is also a direct warning.

2. Input to the excel file

The input values include a driving speed (with an associated stopping distance), 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.

Speed	Driver age and conditions			Visual task			Disability glare			Criteria (minimum)		
Design speed V	Driver age	Transmittance Wind screen	Transmittance Air	Size of object	Intrinsic contrast of object	Glance duration	Daylight Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Interior luminance Lin	Time per factor 10 t10
km/h	23-75 y	%	%	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	60,0	80	100	0,2	-68	0,5	300	0,1	0,25	5		5

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 an associated 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.

In further agreement with CIE 88:2004, the main glare sources at the reference position is caused by daylight and includes glare from luminous surfaces about 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 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. 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.

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 accounted for in ”Visibility of Targets”, Werner Adrian, Transportation research record 1247, http://onlinepubs.trb.org/Onlinepubs/trr/1989/1247/1247-006.pdf.

The calculations include all the details of the visibility model including the influence of the apparent size of the object, the background luminance, the inherent contrast of the object to the background, the influence of disability glare, the influence of the age of the driver, the duration of a glance at 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. The VL value is preset to 5, which is a reasonable value.

The criterion is met by the setting of proper values of the local road surface luminance at each location of the object. At the first location at the tunnel entrance, the road surface luminance is called L_{th} and is normally at its highest. In the following locations, the luminance decreases gradually.

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. However, the glare from daylight applies only for the threshold zone, which makes this zone special.

The adjustments of the road surface luminance profiles from one drive to the next in the iterative procedure mentioned 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 and the other as the road surface luminance at the previous location times F_{10}. Whenever the road surface luminance calculated on the basis of the VL value is lower, 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 inner 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 iterative procedure mentioned in section 1. However, it does not prevent that the iterative procedure 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/m², 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/m², the adaptation takes time; for high values (over some 8.000 cd/m²) 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/m².

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 iterative procedure mentioned in section 1.

6. Results

The main results are shown in figure 3.

Stopping distance	Initial luminance Lth	Interior luminance Lin	VL at tunnel entrance		VL interior zone		Length of threshold zone	Length of transition zone	Time in the transition zone	k factor
			intended	actual	intended	actual				
m	cd/m2	cd/m2	agreement		agreement		m	m	seconds	
100	124	0,73	5,00	5,00	5,00	5,00	100	224	10,08	0,0195

Figure 3: Main results.

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.

Other results are the initial road surface luminance L_{th} at the tunnel entrance and the road surface luminance L_{in} in the interior zone. These are supplemented with the VL values at the tunnel entrance and in the interior zone. The two VL values are equal, unless the optional criterion for the road surface luminance in the interior surface has been applied.

The VL values both as intended and as actually achieved are given. These are equal, when the iterative procedure converges, and this is confirmed by the statement “agreement”. However, as mentioned in section 1, it may occur that the iterative procedure does not converge. If so, the intended and actual VL values will be different and the statement is changed to “disagreement”.

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

Finally, 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 how this value is obtained.

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

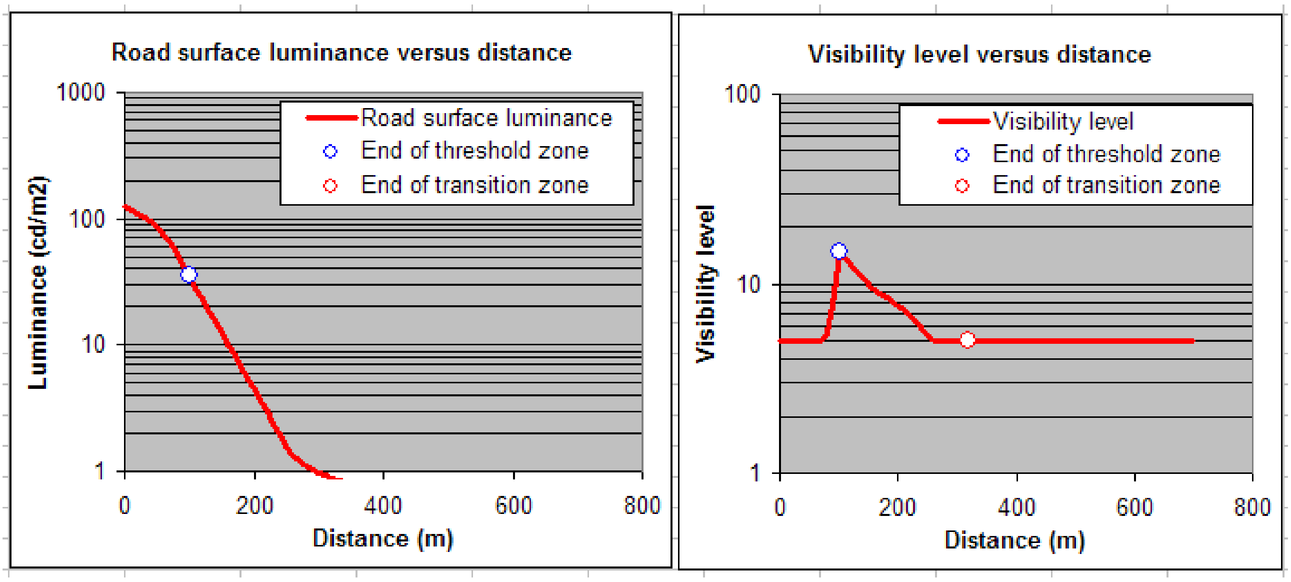


Figure 4: Diagrams with profiles for the road surface luminance and the VL values.

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.

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

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.

This additional user part can be used for instance to see how much an old driver gains by reducing his speed. See figure 5, where the case is that a 60 years old driver has a visibility level 5 when driving 80 km/h. The second driver is 75 years old, but can also obtain a visibility level of almost 5 by reducing his speed to 70 km/h.

Figure 5: Input and results for a second driver.

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		
70	75,0	80	4,99	4,83

There is a more detailed account of the results in annex A.

7. Examples of calculations

Some examples of calculations are presented in annex B.

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.

Finally, the examples in B.4 provide a comparison to recommendations in CIE 88:1990.

Concerning the recommended values of the k factor and the luminance in the inner zone L_{in}, it is argued that the excel file points to a stronger variation with the driving speed than reflected in the recommendations.

The examples in B.4 also include the driving time in the transition zone and results in driving times from 10 to 12 seconds for the range of driving speeds from 60 to 110 km/h. This is less than the 20 seconds drive that is linked to the luminance profile for the transition zone in both CIE 88:1990 and CIE 88:2004. Accordingly, it may be permissible to reduce the length of the transition zone to a degree depending on the driving speed.

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.

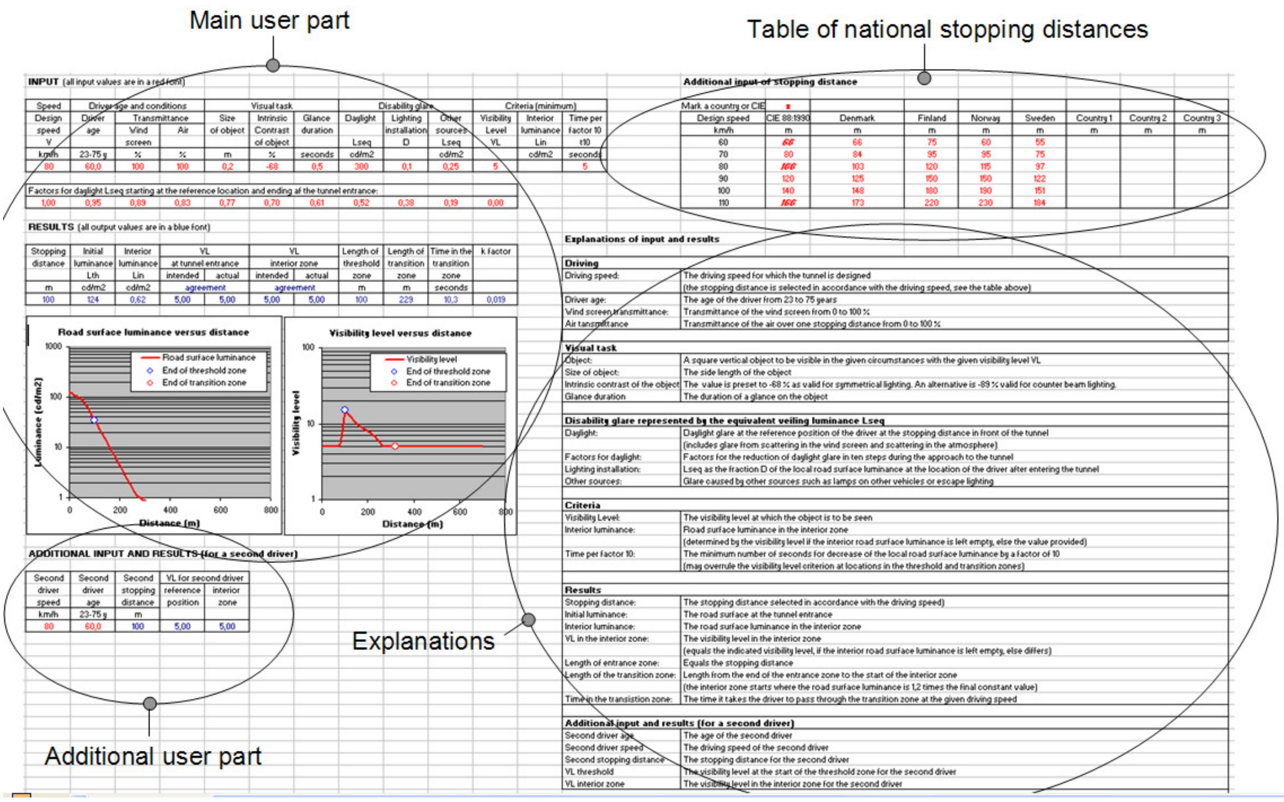


Figure A.1: The page "input and results".

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.

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
km/h	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)

Speed	Driver age and conditions			Visual task			Disability glare			Criteria (minimum)		
Design speed V	Driver age	Transmittance Wind screen	Transmittance Air	Size of object	Intrinsic Contrast of object	Glance duration	Daylight Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Interior luminance Lin	Time per factor 10 t10
km/h	23-75 y	%	%	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	60,0	80	100	0,2	-68	0,5	300	0,1	0,25	5		5

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	Initial luminance Lth	Interior luminance Lin	VL at tunnel entrance		VL interior zone		Length of threshold zone	Length of transition zone	Time in the transition zone	k factor
			intended	actual	intended	actual				
m	cd/m2	cd/m2	agreement		agreement		m	m	seconds	
100	124	0,73	5,00	5,00	5,00	5,00	100	224	10,1	0,019

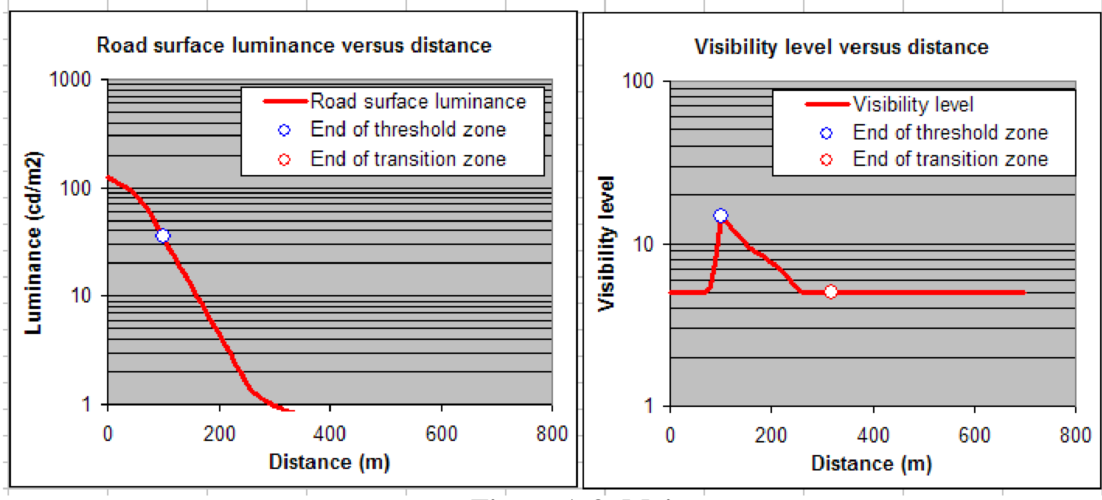


Figure A.3: Main user part.

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.

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

Figure A.4: Additional user part.

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 %
Air tansmittance	Transmittance of the air over one stopping distance from 0 to 100 %
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 objec	The value is preset to -68 % as valid for symmetrical lighting. An alternative is -89 % valid for counter beam lighting.
Glance duration	The duration of a glance on the object
Disability glare represented by the equivalent veiling luminance Lseq	
Daylight:	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:	The visibility level at which the object is to be seen
Interior luminance:	Road surface luminance in the interior zone
	(determined by the visibility level if the interior road surface luminance is left empty, else the value provided)
Time per factor 10:	The minimum number of seconds for decrease of the local road surface luminance by a factor of 10
	(may overrule the visibility level criterion at locations in the threshold and transition zones)
Results	
Stopping distance:	The stopping distance selected in accordance with the driving speed)
Initial luminance:	The road surface at the tunnel entrance
Interior luminance:	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
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 speed and stopping distance

The first input is the design driving speed, either 60, 70, 80, 90, 100 or 110 km/h. The excel file then selects the stopping distance in the table for national stopping distances as explained in A.1.

Speed	Driver age and conditions			Visual task			Disability glare			Criteria (minimum)		
Design speed V	Driver age	Transmittance Wind screen	Air	Size of object	Intrinsic Contrast of object	Glance duration	Daylight Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Interior luminance Lin	Time per factor 10 t10
km/h	23-75 y	%	%	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	60,0	80	100	0,2	-68	0,5	300	0,1	0,25	5		5

Mark a country or CIE	x							
Design speed	CIE 88:199	Denmark	Finland	Norway	Sweden	Country 1	Country 2	Country 3
km/h	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.

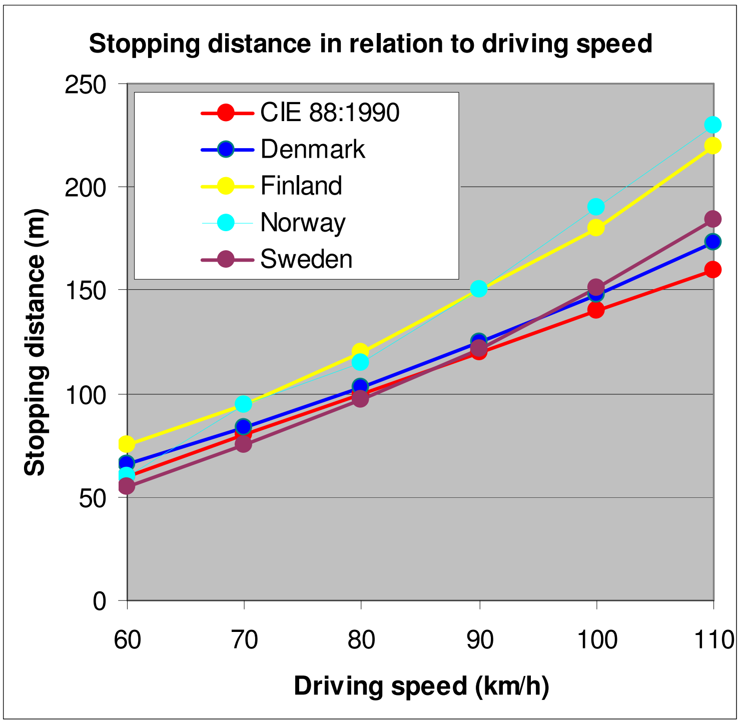


Figure A.7: Stopping distance in relation to driving speed.

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.

It is pointed out that there is a maximum stopping distance as demonstrated in figure A.8.

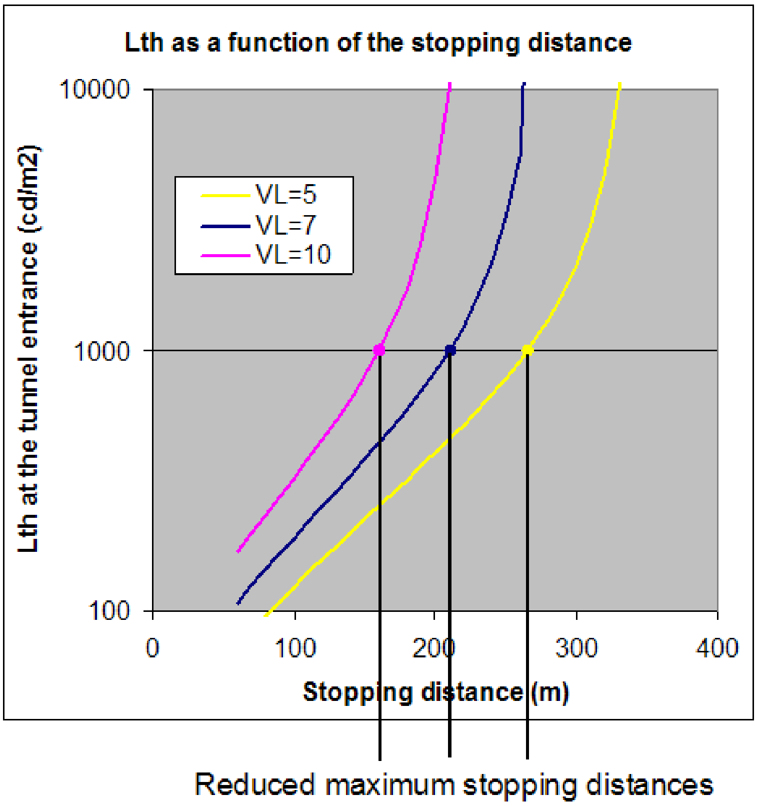


Figure A.8: L_{th} as a function of the stopping distance for a 60 year old driver.

Figure A.8 shows the threshold luminance L_{th} as a function of the stopping distance. Depending on the visibility level VL, the stopping distance has a maximum, where the curve turns vertical.

It is of course futile to set a stopping distance that exceeds the maximum at the relevant visibility level. As the curves start bending upwards, before the maximum stopping distances are met, even a stopping distance close to maximum should be avoided. Therefore, some reduced maximum stopping distances are indicated in figure A.8 and also given in table A.1.

Table A.1: Reduced maximum stopping distances at different visibility levels VL.

Visibility level VL	Reduced maximum stopping distances
5	266 m
7	211 m
10	161 m

As stopping distances of more than 200 m need to be considered, the visibility level VL should not exceed 5. Alternatively, the size of the object can be increased.

Figure A.8 applies for a 60 year old driver and the other input values shown in figure A.3. The age of the observer does not affect the reduced maximum stopping distances.

A.3 Driver age and conditions

The second group of input relates to the driver age and conditions and includes:

- the age of the driver,
- the transmittance of the wind screen,
- the transmittance of the air (atmosphere),

Speed	Driver age and conditions			Visual task			Disability glare			Criteria (minimum)		
Design speed V	Driver age	Transmittance Wind screen	Air	Size of object	Intrinsic Contrast of object	Glance duration	Daylight Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Interior luminance Lin	Time per factor 10 t10
km/h	23-75 y	%	%	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	60,0	80	100	0,2	-68	0,5	300	0,1	0,25	5		5

The need for luminance increases with the age of the driver as indicated by an age factor AF1 shown in figure A.9. At the same time, L_{seq} values representing disability glare increase by an age factor AF2 also shown in figure A.9.

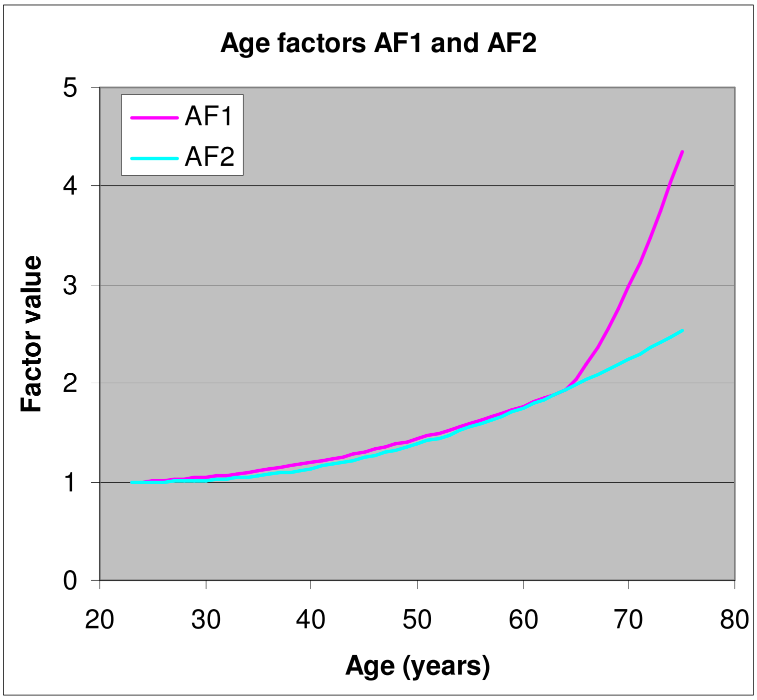


Figure A.9: Increase of the age factors AF1 and AF2 with age.

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.9 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.

Absorption in the wind screen, as described by a transmittance less than 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 inner zone. The wind screen transmittance is preset to 80 %.

Absorption in the air is also described by an air transmittance value 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.4 The visual task

The third 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.

Speed	Driver age and conditions			Visual task			Disability glare			Criteria (minimum)		
Design	Driver	Transmittance		Size	Intrinsic	Glance	Daylight	Lighting	Other	Visibility	Interior	Time per
speed	age	Wind	Air	of object	Contrast	duration		installation	sources	Level	luminance	factor 10
V		screen			of object		Lseq	D	Lseq	VL	Lin	t10
km/h	23-75 y	%	%	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	60,0	80	100	0,2	-68	0,5	300	0,1	0,25	5		5

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.

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 se a reduced 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 % valid 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.

NOTE: 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, $L_{road\ surface} = q_C \times E_v$.

Accordingly, $C = L_{object}/L_{road\ surface} - 1 = (\rho \times E_v/\pi)/(q_C \times E_v) - 1 = \rho//(q_C \times \pi) - 1$

Finally, CIE 88:2004 sets ρ to 0,2 and introduces standardized figures 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.10.

Figure A.10: The polarization factor as a function of the object size and the background luminance.

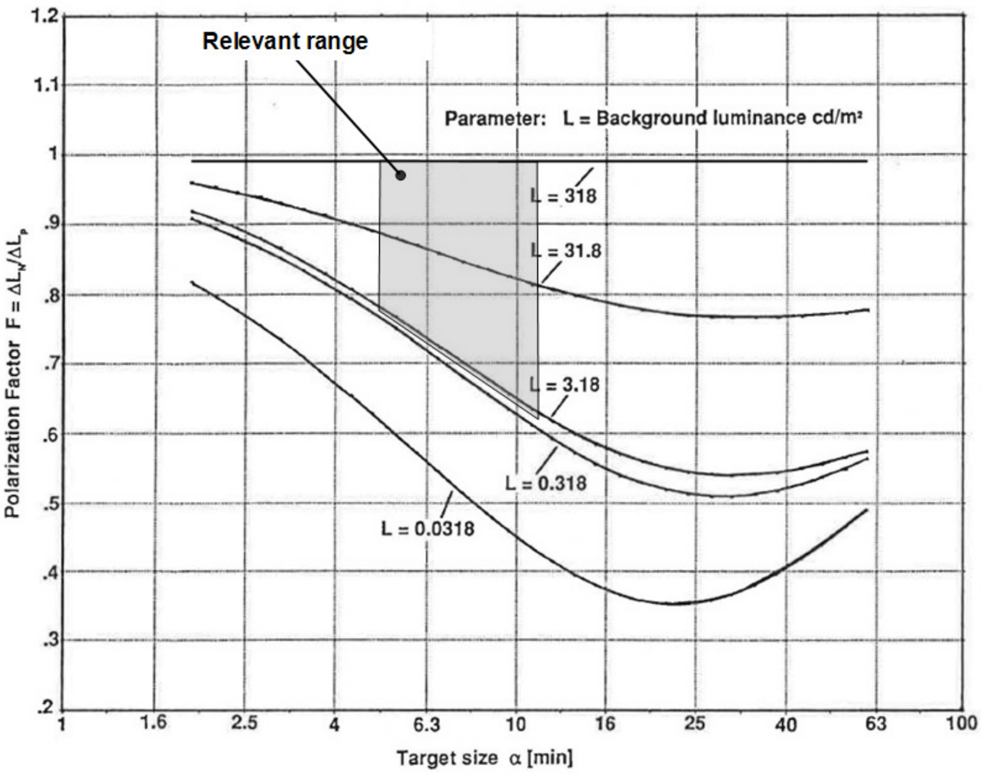


Figure A.10 is a copy of a diagram in the paper "Visibility of Targets" by Werner Adrian, to which the range relevant for tunnel lighting has been added. It can be seen that the factor is close to 1 for the high luminance levels that are relevant for the threshold zone, but significantly lower for the 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.

The influence of the exposure time is described by a factor to the visibility level. The factor has a value of 1 at 2 seconds, but decreases with decreasing observation 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 factor is not reduced by much.

A.4 Disability glare

The fourth 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.

Speed	Driver age and conditions			Visual task			Disability glare			Criteria (minimum)		
Design	Driver	Transmittance		Size	Intrinsic	Glance	Daylight	Lighting	Other	Visibility	Interior	Time per
speed	age	Wind	Air	of object	Contrast	duration		installation	sources	Level	luminance	factor 10
V		screen			of object		Lseq	D	Lseq	VL	Lin	t10
km/h	23-75 y	%	%	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	60,0	80	100	0,2	-68	0,5	300	0,1	0,25	5		5

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

Together with L_{seq} comes a string of 11 relative 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 values 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.

CIE 88:2004 provides L_{seq} values for veiling luminance caused by scatter in the air and the wind screen as shown in table A.2. L_{seq} values selected from the table are to be added to the above-mentioned L_{seq} value for daylight.

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

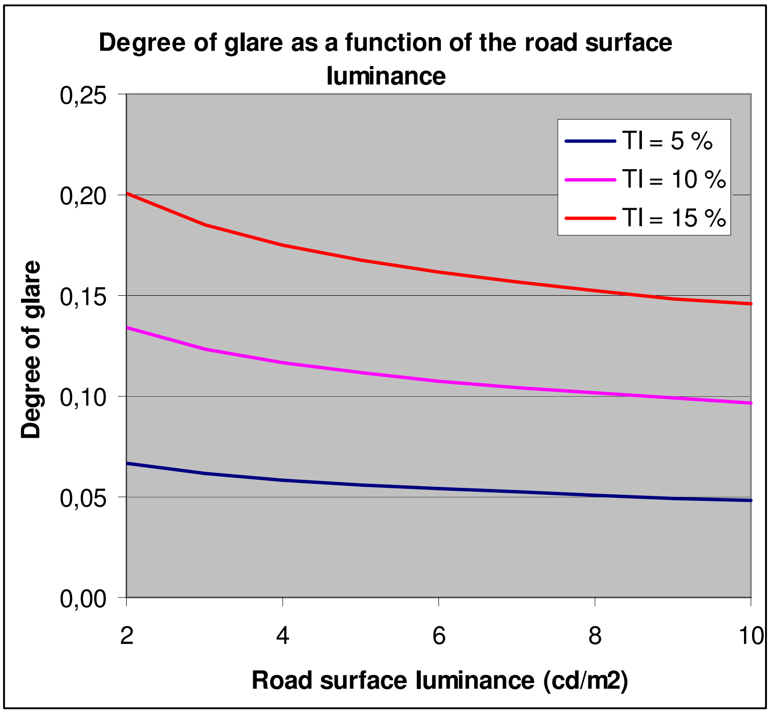
Veiling levels	High	Medium	Low
Atmospheric veiling luminance (cd/m^2)	300	200	100
Windscreen veiling luminance (cd/m^2)	200	100	50

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.11 in dependence of the road surface luminance and for the above-mentioned TI values.

Figure A.11: Degree of glare as a function of the road surface luminance.



Judged from figure A.11, 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.

Other glare may be caused by other glare sources in the tunnel, for instance 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 among else 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 0,24 cd/m^2.

A.5 Input data for criteria

The last group of input data relates to the criteria for the road surface luminance.

Speed	Driver age and conditions			Visual task			Disability glare			Criteria (minimum)		
Design speed V	Driver age	Transmittance Wind screen	Transmittance Air	Size of object	Intrinsic Contrast of object	Glance duration	Daylight Lseq	Lighting installation D	Other sources Lseq	Visibility Level VL	Interior luminance Lin	Time per factor 10 t10
km/h	23-75 y	%	%	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	60,0	80	100	0,2	-68	0,5	300	0,1	0,25	5		5

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, and on the maximum stopping distances that can be used, refer to A.2.

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 inner zone equal to the input value. This VL value is applied in the transition zone as well as in the inner zone.

The last criterion concerns is 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.6 Results of calculations

The final result is the luminance profile for the road surface. 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 stopping distance for the relevant driving speed,
b. the luminance at the tunnel entrance in the threshold zone L_{th},
c. the luminance in the interior zone L_{in},
d. the intended VL value,
e. the actual VL value for the reference location of the driver with the object placed at the tunnel entrance,
f. the intended VL value in the interior zone (deviates from the minimum VL value, when the L_{in} value has been set),
g. the actual VL value in the interior zone,
h. the length of the threshold zone (equal to the stopping distance),
i. 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),
j. the duration of driving in the transition zone,
k. the k factor (based on an estimated value of L_{20}).

Stopping distance	Initial luminance Lth	Interior luminance Lin	VL at tunnel entrance		VL interior zone		Length of threshold zone	Length of transition zone	Time in the transition zone	k factor
			intended	actual	intended	actual				
m	cd/m2	cd/m2	agreement		agreement		m	m	seconds	
100	124	0,73	5,00	5,00	5,00	5,00	100	224	10,1	0,019

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

The initial luminance L_{th} is the road surface luminance at the tunnel entrance, while the interior luminance L_{in} is the luminance in the interior zone.

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. The visibility level VL in the interior zone is handled in the same manner.

The VL values generally agree, except when it is not possible to supply the intended VL values in view of other input values, refer to A.2. If so, the disagreement is stated.

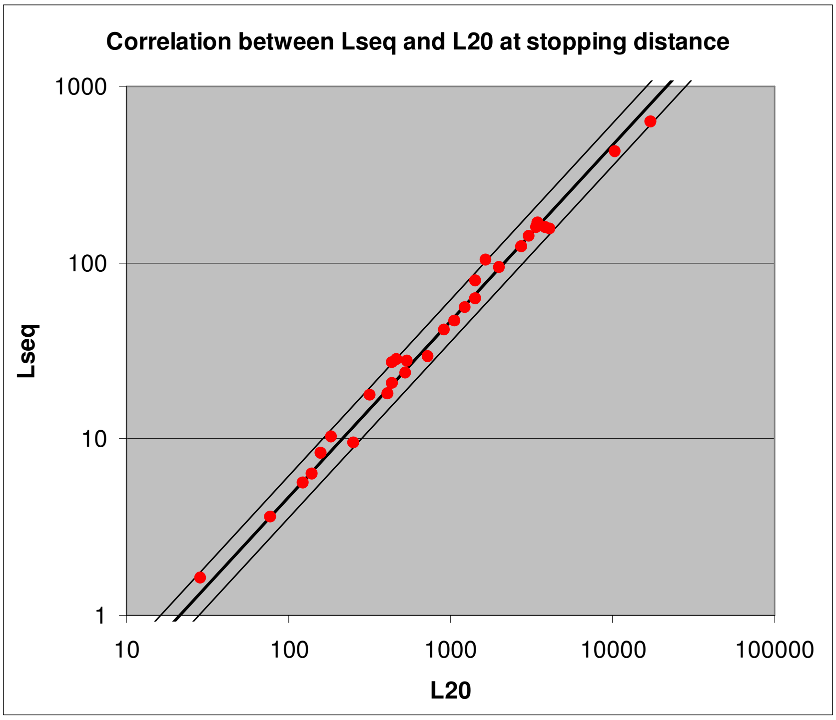
The last four results have been added for easy comparison to CIE 88:1990 and CIE 88:2004.

Only the k factor needs to be explained. It is defined in CIE 88:1990 as the ratio between the L_{th} and the L_{20} values. 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.12, which also shows a regression line representing a ratio of 0,047. Accordingly, L_{20} is estimated by $L_{20} = L_{seq}/0,047$.

Note: The thin lines represent twice a standard deviation of 15 %.

Figure A.12: Correlation between of L_{seq} and L_{20} for 15 tunnels in Norway measured in both directions.



Annex B: Examples of calculation results
B.1 Introduction

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

The starting point for these examples is use of the preset input data shown in figure A.3, except for variations that 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.

Finally, the examples in B.4 provide a comparison to recommendations in CIE 88:1990 and CIE 88:2004.

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 inner zone, and a weak influence on the length of the transition zone. Similar results are obtained for other driving speeds.

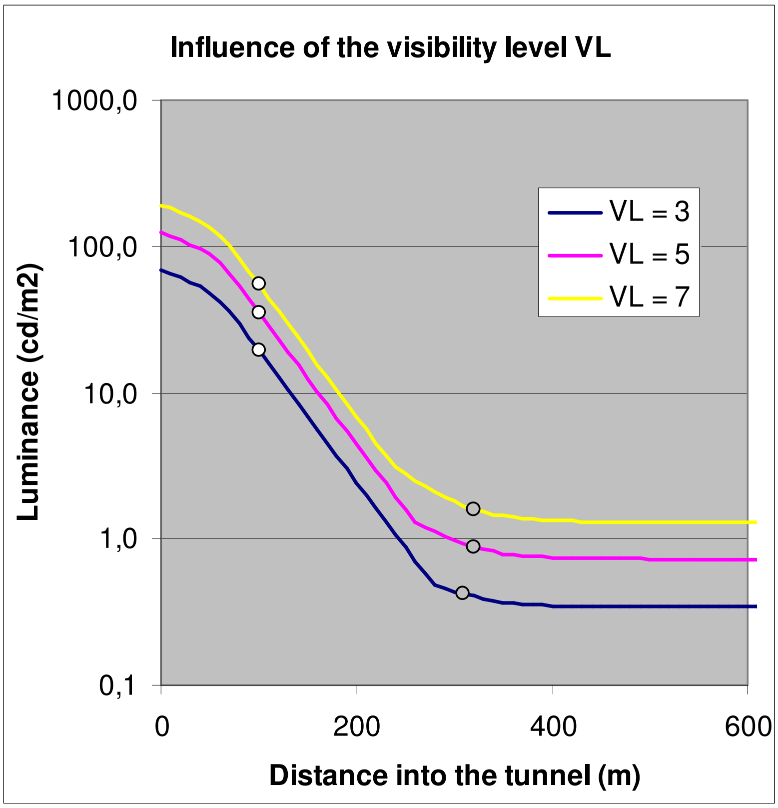


Figure B.1 Luminance profiles for different values of the visibility level VL.

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.

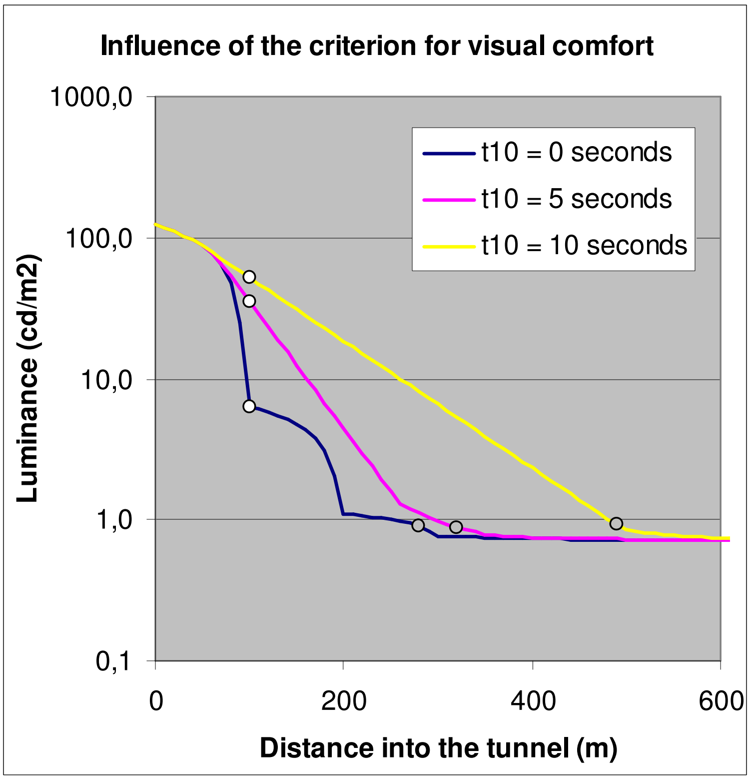
For a value of t_{10} of 10 seconds, the luminance profile is forced to become more wide by the criterion. This leads to a prolongation of the transition zone.

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



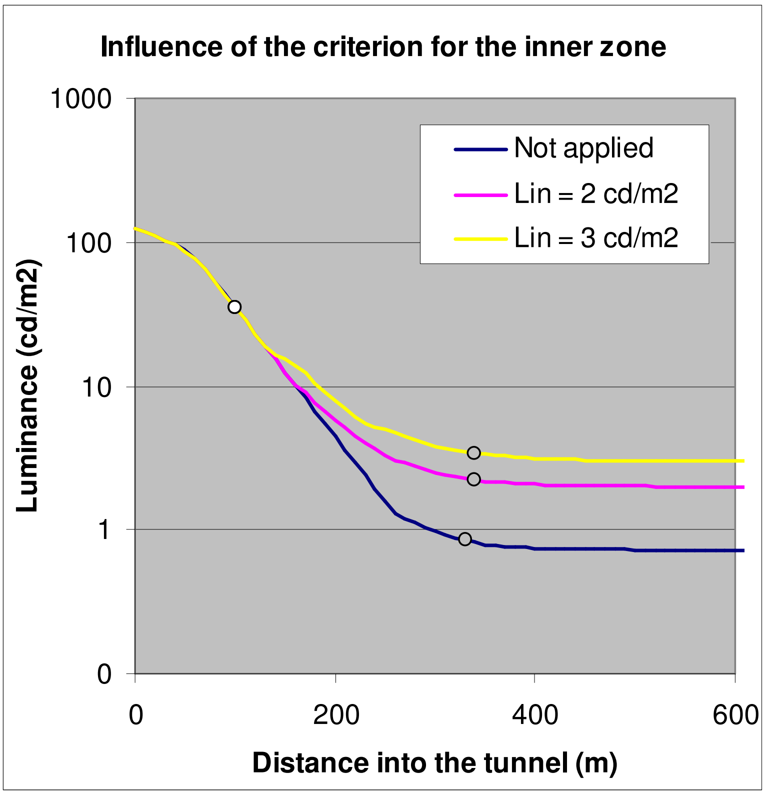
B.2.3 Luminance in the interior zone

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 values 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.

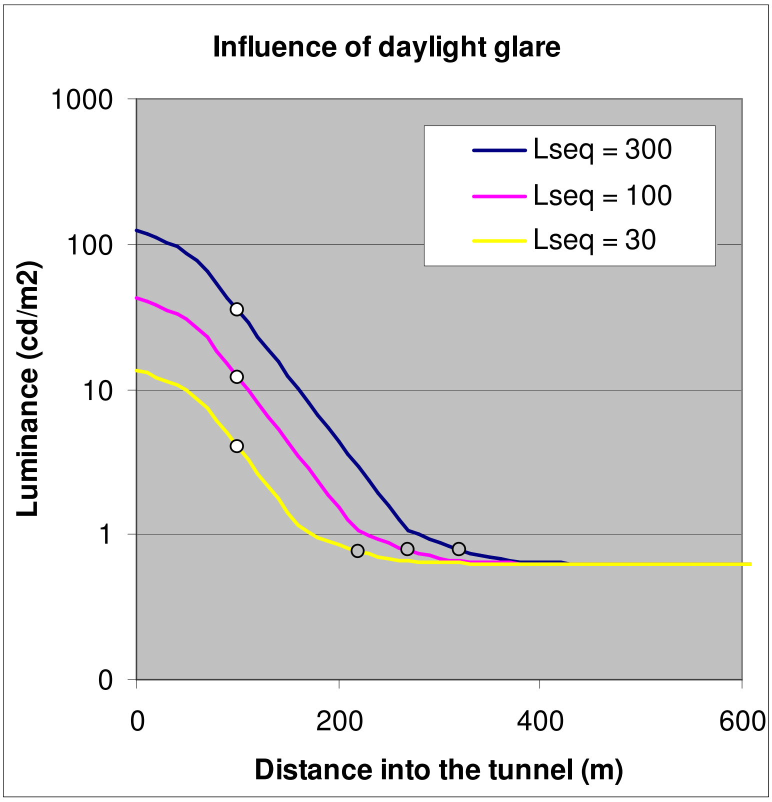


Figure B.4: Luminance profiles for different settings of L_{seq}.

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 inner zone L_{in}. It is actually the stopping distances associated with the driving speeds, not the driving speeds themselves, that 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.

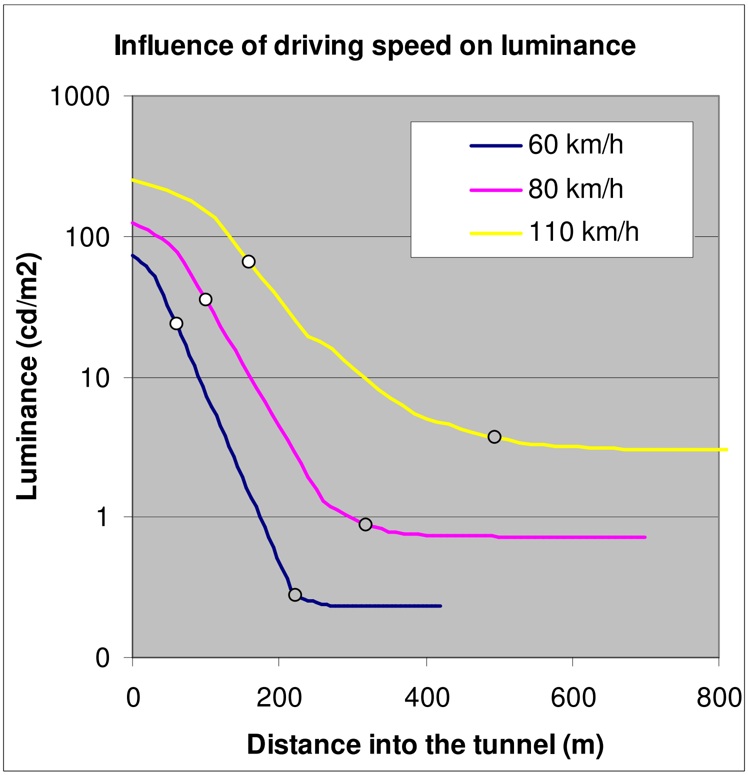


Figure B.5: Luminance profiles for different settings of the driving speed.

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 inner zone L_{in}. There is no influence on the length of the transition zone

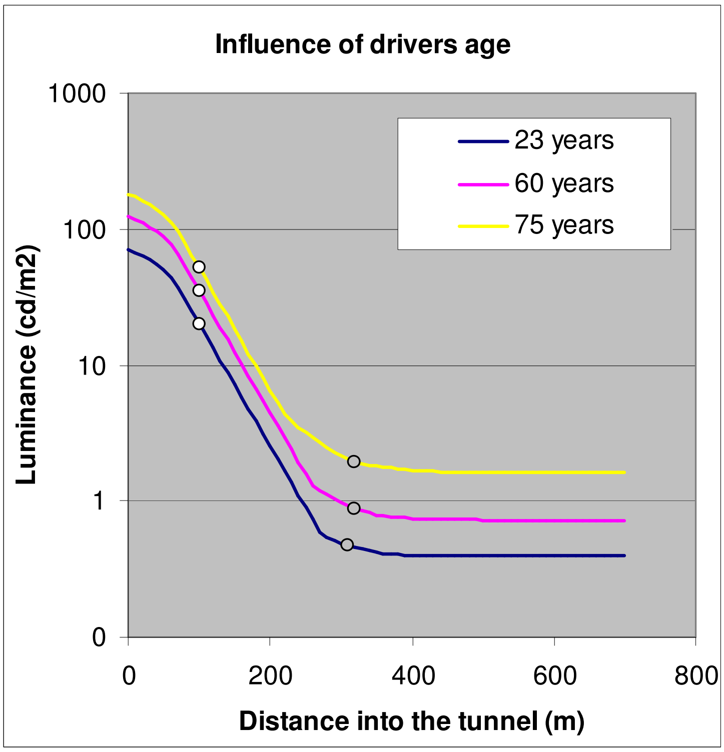


Figure B.6: Luminance profiles for different ages of the driver.

B.4 Comparison to recommendations in CIE 88:1990 and CIE 88:2004

B.4.1 The initial luminance in the threshold zone

CIE 88:1990 has the recommendations for the initial luminance in the threshold zone L_{th} in proportion to the L_{20} value (k factor) shown in figure B.7.

Figure B.7: 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 ratio L/E_V in figure B.7 is the contrast revealing coefficient q_C defined in CIE 88:2004. Accordingly, the CIE 88:1990 recommendations for the k factors are presented again in table B.1. These k factors can be compared to the k factors shown in table B.2, as supplied by the excel file for a 60 old driver and the actual values of q_C recommended in CIE 88:2004.

Table B.1: CIE 88:1990 recommendations for the k factors.

Stopping distance	Symmetrical lighting system ($q_C \leq 0,2$)	Counter beam lighting system ($q_C \geq 0,6$)
	$k = L_{th}/L_{20}$	$k = L_{th}/L_{20}$
60 m	0,050	0,040
100 m	0,060	0,050
160 m	0,100	0,070

Table B.2: Calculated k factors for a 60 old driver and the actual values of q_C of CIE 88:2004.

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	0,011	0,009
100 m	0,020	0,014
160 m	0,040	0,027

It can be seen that the calculated k factors of table B.2 are much smaller than the values recommended in CIE 88:1990. This is the case even for a driver of 75 years.

The question is then if the k factors of CIE 88:1990 are unrealistic? The answer is that these k factors probably are realistic, when taking other glare sources - such as glare in the wind screen and in the atmosphere - into account. This can be verified in calculations.

However, one matter remains, that 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.

B.4.2 The luminance in the interior zone

CIE 88:1990 and CIE 88:2004 by give recommendations for the luminance in the interior zone L_{in}. For simplicity, only those CIE 88:1990 are shown here, refer to figure B.8.

Interior zone average road surface luminance cd/m²			
	Traffic flow		
stopping Distance S.D.	Low ≤ 100 vehicles/h	Medium > 100 vehicles/h < 1 000 vehicles/h	Heavy ≥ 1 000 vehicles/h
160 m	5	10	15
100 m	2	4	6
60 m	1	2	3

Figure B.8: CIE 88: 1990 recommendations for the luminance in the inner zone.

There is no good way to reproduce the values of figure B.8 by calculations with the excel file for two reasons:

a. calculated values tend to be lower,
b. calculated values show a much larger variation with the stopping distance.

Re. a: For the stopping distance of 160 m and an age of the driver of 75 years, the calculated value of L_{in} is 7,5 cd/m^2. For the other stopping distances of 100 m and 60 m, calculated values of L_{in} are lower than the values of figure B.8 for low traffic flow. This may indicate that there are other considerations behind the values of figure B.8 than just visual performance.

Re. b: Calculated values of Lin vary by a factor of approximately 15 with the stopping distance in the range from 60 to 160 m. The values of figure B.8 vary by a factor of 3 only. This may indicate that the stopping distance has a stronger influence on the road surface luminance needed in the inner zone, than reflected by the L_{in} values of CIE 88:1990.

B.4.3 The driving time in the transition zone

CIE 88:1990 and CIE 88:2004 both define a luminance profile in the inner zone that involves a driving time of 20 seconds. The same profile is given in CIE 88:2004 as well. For comparison, figure B.9 shows the time in the transition zone as a function of the driving speed for two settings of the t_{10} value.

Figure B.9: Time in the transition zone for two settings of the L_{10} value.

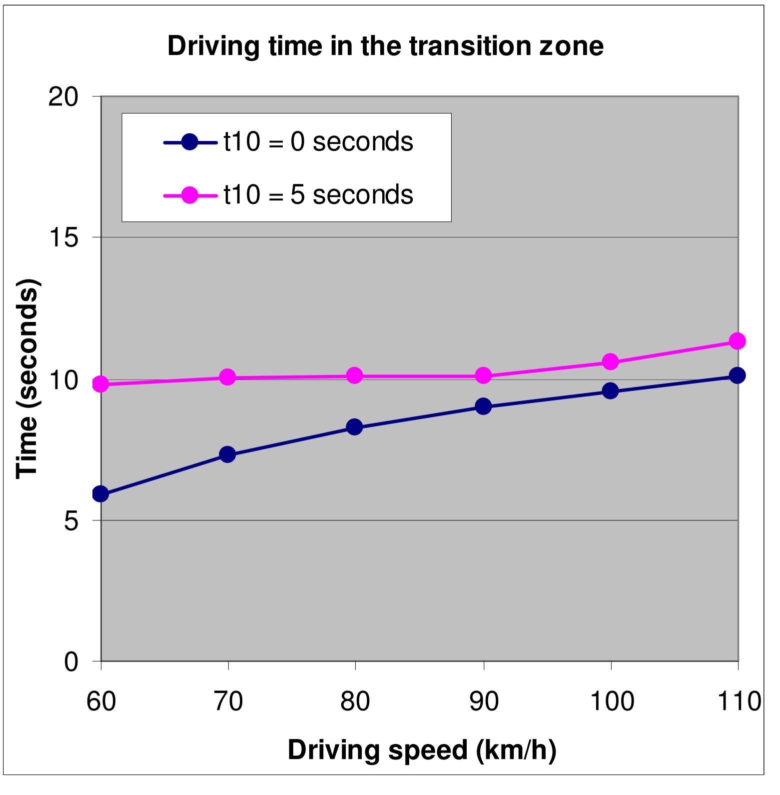


Figure B.9 illustrates that the criterion for visual comfort prevents that the driving times for the low driving speeds become very short.

When taking this criterion into account, figure B.9 shows driving times from approximately 10 to 12 seconds as compared to the above-mentioned 20 seconds. Therefore, it should be possible to use shorter transition zones.