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.

Report

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. The road surface luminance at the object is determined in accordance with the above-mentioned criteria and other input values as described in the following. The luminance values form a luminance profile of the road surface luminance.

The luminance profile is actually determined in an iterative procedure that involves 20 repetitions of the drive, each of them with adjustments of the individual road surface luminance values. It is necessary to use such a procedure because the road surface luminance at a particular location depends on the road surface luminance values both before and after the location.

2. Criterion for the road surface luminance in the threshold zone

The threshold zone starts at the tunnel entrance and has a length of one stopping distance at the relevant driving speed.

In this zone, the driver is approaching the tunnel entrance, starting at the reference position and ending at the tunnel entrance in ten steps. The driver is exposed to glare from the daylight as describe by values of the equivalent veiling luminance L_{seq} that are gradually decreasing as the driver approaches the tunnel entrance.

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

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

It is pointed out that the object is assumed to have a constant contrast to the road surface and that the road surface luminance is represented by a single value at each location. The contrast value is set in the input.

This means that the visibility level is used as a general measure of the visibility conditions, without taking details relating to transverse locations of the object and the precise directionality of the lighting into account.

3. Criterion for the road surface luminance in the interior zone

The road surface luminance decreases gradually in the transition zone until it reaches a constant level. This marks the start of the interior zone with a constant road surface luminance L_{in}.

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

The value of L_{in} is calculated by the same method as for the luminance in the threshold zone, by taking glare and other circumstances into account.

Glare is caused by the luminaires lighting installation itself, and by other light sources. These are in particular the headlamps of oncoming vehicles, but may include other glare sources, for instance marker or escape lights.

The glare from the lighting installation is described by a value of the L_{seq}, which is derived as a fraction of the road surface luminance. This fraction is called the degree of glare D. Glare by other glare sources is described by a fixed value of the L_{seq}.

It is recognized that L_{in} values as supplied in CIE 88: 1990 may be selected by other criteria than those described above. Therefore, as an option, the desired value of L_{in} can be set directly. If this is done, 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. If so, this VL value is also applied in the transition zone.

4. Criteria for the road surface luminance in the transition zone

The road surface luminance in the transition zone is made to comply with the same minimum visibility level VL as in the interior zone. Glare are from the same sources as described for the inner zone.

However, one more criterion is applied - 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. This criterion is also applied in the other zones and may have an effect in the threshold zone as well, but not in the interior zone.

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, indicates 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 minimum t_{10} is assumed to relate to visual comfort. It is used as described below.

In 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 a minimum luminance determined as the luminance at the previous location times a factor that relates to the t_{10} value. Whenever the luminance calculated on the basis of the VL value is lower than the minimum luminance, it is replaced by the minimum luminance. This leads to a local raise of the VL value above the minimum.

Note: This above-mentioned factor is predetermined as 10 to the power of minus $\Delta t/t_{20}$, where Δt is the time interval between successive locations.

5. Input values and results

Input values and results are described in detail in annex A, which also describes the influence of the various input values on the results. Some of the results are introduced in order to obtain comparison to the recommendations of CIE 88:1990.

It is suggested to use preset values for some inputs, as these form a general measure of the visibility conditions and lead to some agreement between the calculation results and the recommendations in CIE 88:1990. These input values are the size and contrast of the object, the exposure time and the visibility level. However, when assuming long stopping distances it may be necessary to reduce the visibility level.

Other input values can be varied from case to case. These are for instance the driving speed and its associated stopping distance, and the age of the driver.

The authors are not sure about the validity of the age factor values. The data are old, and elderly persons may be in better health than when the age factor values were established. Operations for cateracts should also be a factor.

However, the age factor values are used as they are, but instead of setting a fixed age, it is investigated what ages are permissible in view of the recommendations of CIE 88:1990. Additionally, it is assumed that elderly drivers reduce their driving speeds, when they feel uncomfortable at the nominal speed. To this purpose, the excel file has been equipped with additional input and results for a second driver, that may be of a different age and driving with a different speed.

6. Examples of calculations

Some examples of calculations are presented in annex B.

The examples include the influence of the criteria for visual performance, visual comfort and the optional criterion for the luminance in the inner zone.

The examples also include the influence of the threshold luminance L_{th}, the driving speed and the age of the driver.

Finally, the examples include comparisons 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 result is that a tunnel intended for the highest driving speed of 110 km/h allows that only young drivers can cope with the approach to the tunnel and with the drive in the inner zone. For a tunnel intended for the middle speed of 80 km/h, the allowance is extended to drivers of some age, while a tunnel intended for the lowest speed of 60 km/h does allow for drivers of a high age.

It is assumed that the levels of lighting have been set like this for practical and economical reasons and that drivers of age compensate by reducing their speeds, if uncomfortable at the full speed. It is demonstrated that reductions of the speed by 10 or at most 20 km/h do allow for drivers of a high age like 75 years or even higher.

The examples also include the driving time in the transition zone and result in driving times from 11 to 17 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 CIE 88: 1990 luminance profile for the transition zone. Accordingly, it may be permissible to reduce the length of the transition zone to a degree depending on the driving speed.

Note: The authors are of course aware of CIE 88:2004, but prefer to compare to the older version for a number of reasons. CIE 88:1990 is probably still the basis for national tunnel lighting standards in many countries, it covers much of CIE 88:2004, and it is more simple to relate to.

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.

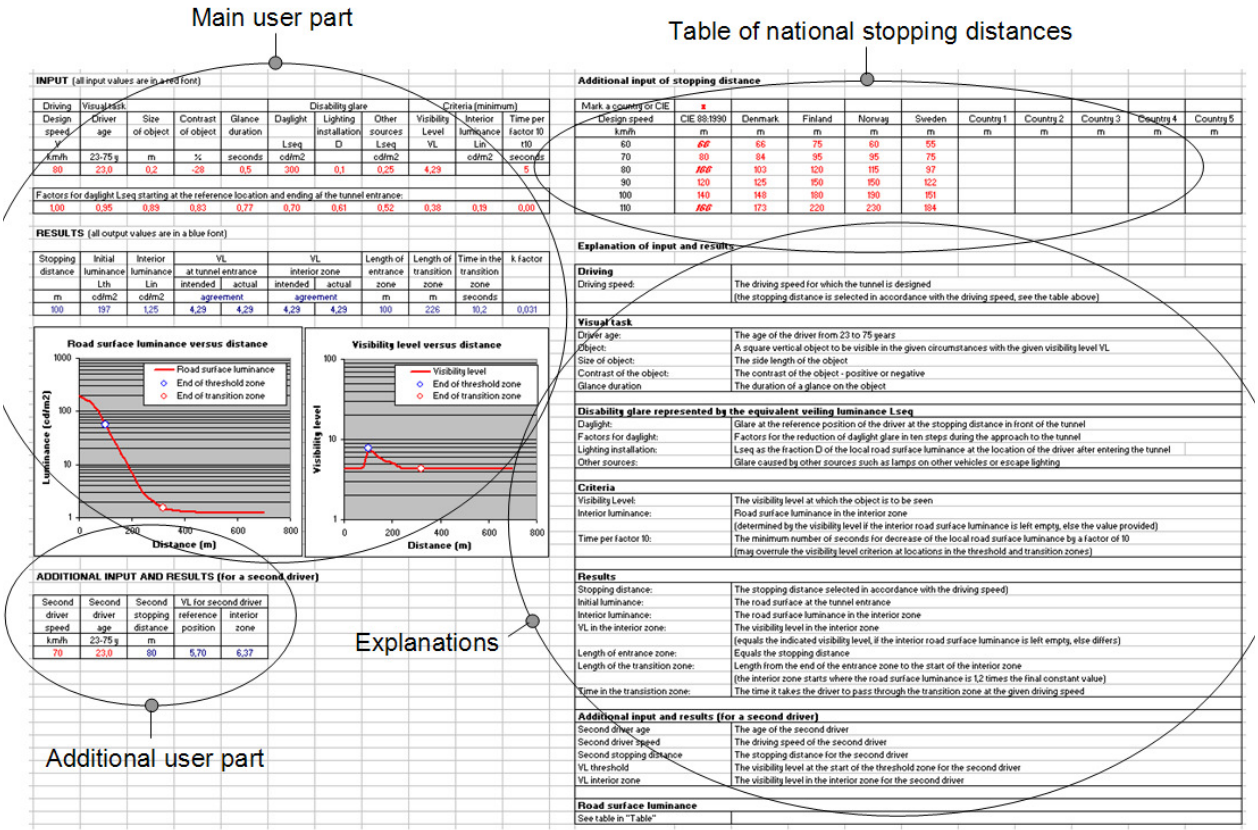


Figure A.1: The page "input and results".

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	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 (minimum)		
Design speed	Driver age	Size of object	Contrast of object	Glance duration	Daylight	Lighting installation	Other sources	Visibility Level	Interior luminance	Time per factor 10
V					Lseq	D	Lseq	VL	Lin	t10
km/h	23-75 y	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	23,0	0,2	-28	0,5	300	0,1	0,25	4,29		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	Interior luminance	VL at tunnel entrance		VL interior zone		Length of threshold zone	Length of transition zone	Time in the transition zone	k factor
	Lth	Lin	intended	actual	intended	actual				
m	cd/m2	cd/m2	agreement		agreement		m	m	seconds	
100	197	1,25	4,29	4,29	4,29	4,29	100	226	10,2	0,031

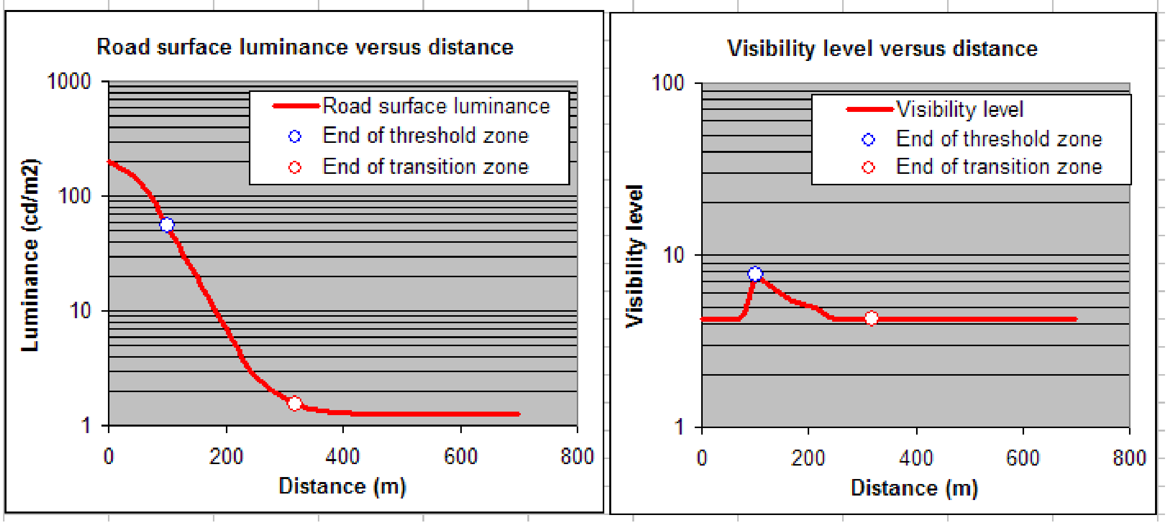


Figure A.3: Main user part.

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.

ADDITIONAL 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	23,0	80	5,70	6,37

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.

Explanation of input and results	
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)
Visual task	
Driver age:	The age of the driver from 23 to 75 years
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
Contrast of the object:	The contrast of the object - positive or negative
Glance duration	The duration of a glance on the object
Disability glare represented by the equivalent veiling luminance Lseq	
Daylight:	Glare at the reference position of the driver at the stopping distance in front of the tunnel
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 “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.

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

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

A.2 The driving speed and the stopping distance

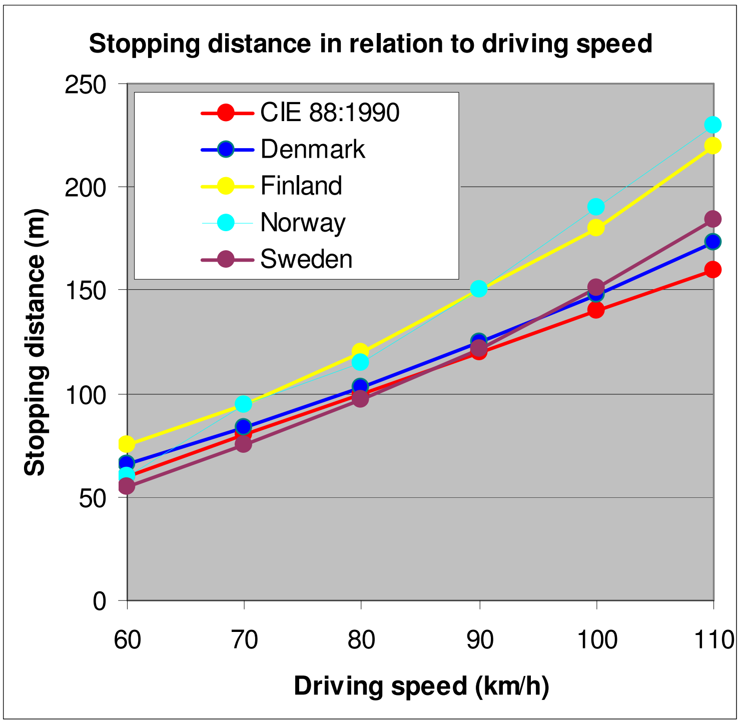
The first input is the design driving speed, either 60, 70, 80, 90, 100 or 110 km/h. The excel file then selects the stopping distance in the table for national stopping distances as explained in A.1.

Driving	Visual task				Disability glare			Criteria (minimum)		
Design speed V	Driver age	Size of object	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	23.0	0.2	-28	0.5	300	0.1	0.25	4.29		5

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.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.

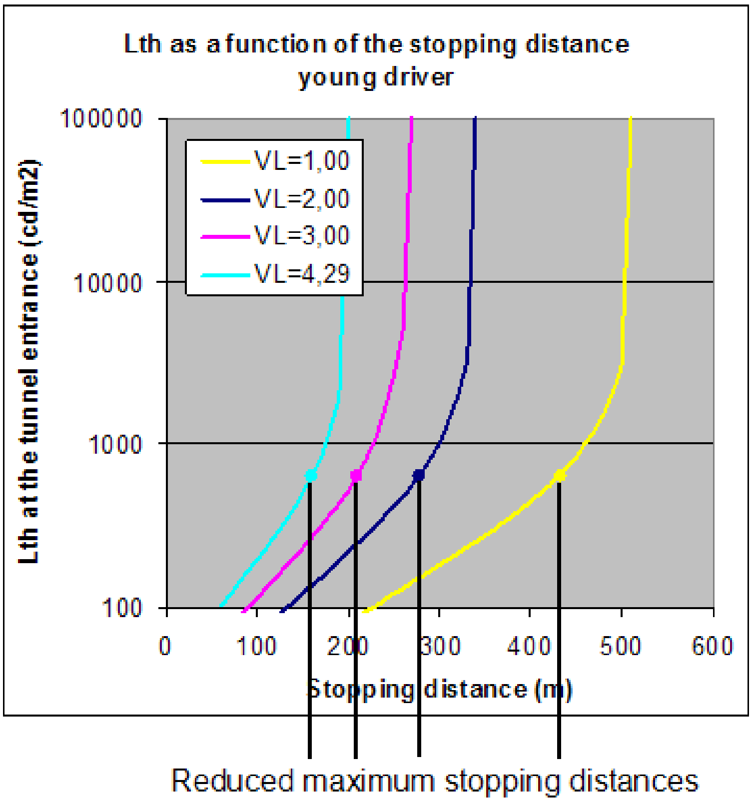


The driving speed has an influence on results only through the criterion for visual comfort, so that a higher driving speed in itself may lead to some prolongation of the transition zone.

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 whose value depend on other input values. This applies both for the threshold zone and the inner zone, but is demonstrated only for the luminance value L_{th} at the tunnel entrance. See figure A.8, which shows L_{th} as a function of the stopping distance. The figure applies for a young driver and the other input values shown in figure A.3.

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



Depending on the visibility level VL, the stopping distance has a maximum, where the curve turns vertical.

For the basic VL value of 1, the maximum stopping distance represents the smallest apparent size of the object that can be discriminated by the human eye in otherwise good conditions of observation. For higher values of VL, the maximum stopping distances are shorter.

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
1,00	432 m
2,00	278 m
3,00	210 m
4,29	160 m

Figure A.9 shows the same diagram as in figure A.8, but for 60 year old driver. It is interesting that this figure shows higher L_{th} values in order to compensate for the age of the driver, but that the maximum stopping distances and the reduced maximum stopping distances are the same as those in figure A.8.

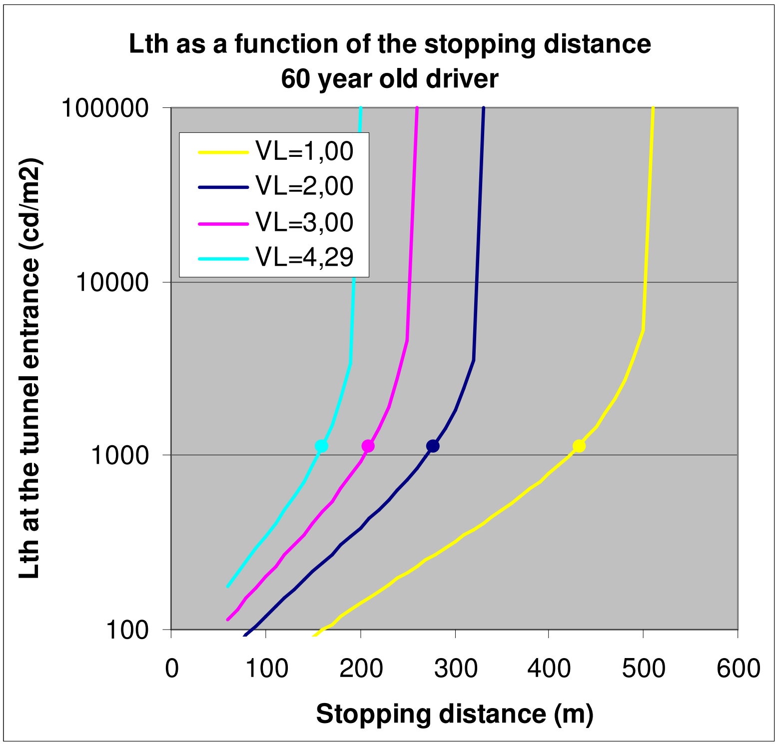


Figure A.9: L_{th} as a function of the stopping distance for 60 year old driver.

This shows that the largest stopping distances shown in figures A.2 and A.7 – in particular those of 220 and 230 m at 110 km/h for respectively Norway and Finland – cannot be applied unless the visibility level is reduced to less than 3. Alternatively, the size of the object can be increased.

The stopping distances labelled CIE 88:1990 can, on the other hand, be applied with a visibility level of 4,29. These stopping distances, and the visibility level of 4,29, are used for the examples shown in the annex B.

A.3 The visual task

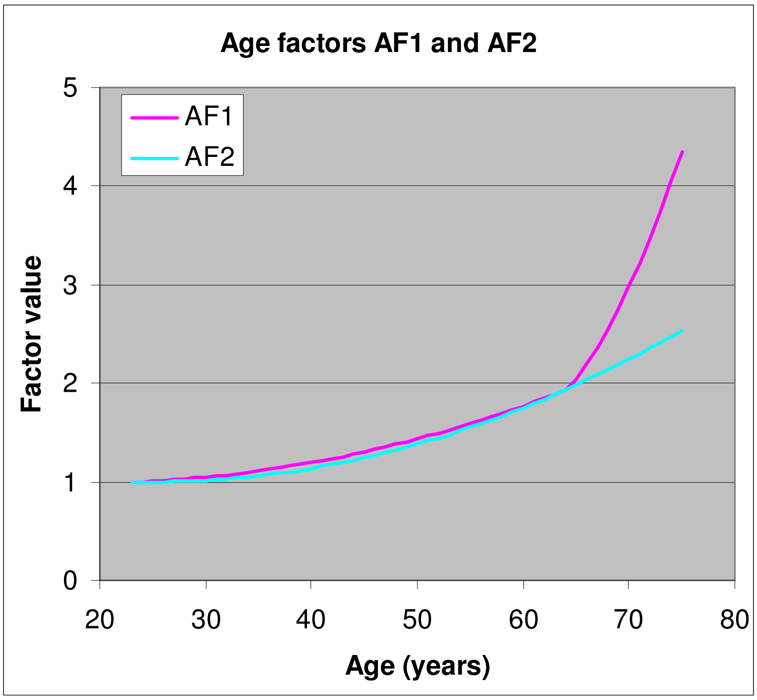
The next group of input relates to the visual task and includes:

- the age of the driver,
- the size of the object, which is assumed to be square and vertical,
- the contrast of the object to the road surface forming the background,
- the exposure time of the object or glance duration.

Driving	Visual task				Disability glare			Criteria (minimum)		
Design speed	Driver age	Size of object	Contrast of object	Glance duration	Daylight	Lighting installation	Other sources	Visibility Level	Interior luminance	Time per factor 10
V					Lseq	D	Lseq	VL	Lin	t10
km/h	23-75 y	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	23,0	0,2	-28	0,5	300	0,1	0,25	4,29		5

The need for luminance increases with the age of the driver as indicated by an age factor AF1 shown in figure A.10. At the same time, L_{seq} values representing disability glare increases by an age factor AF2 also shown in figure A.10.

Figure A.10: 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.10 indicates that age has a strong influence. For the highest age of 75 years covered in figure A.10, the value of AF1 is 4,34, while the value of AF2 is 2,53.

The size of the object is set to 0,2 m, which is the size normally assumed in studies of visibility. It is also 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 contrast of the object is preset to -28 %, which is also the contrast introduced in CIE 88:2004.

The excel file does an initial calculation of the visibility level as if the contrast is positive. If this is really the case, no correction is applied. If, on the other hand, 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.11.

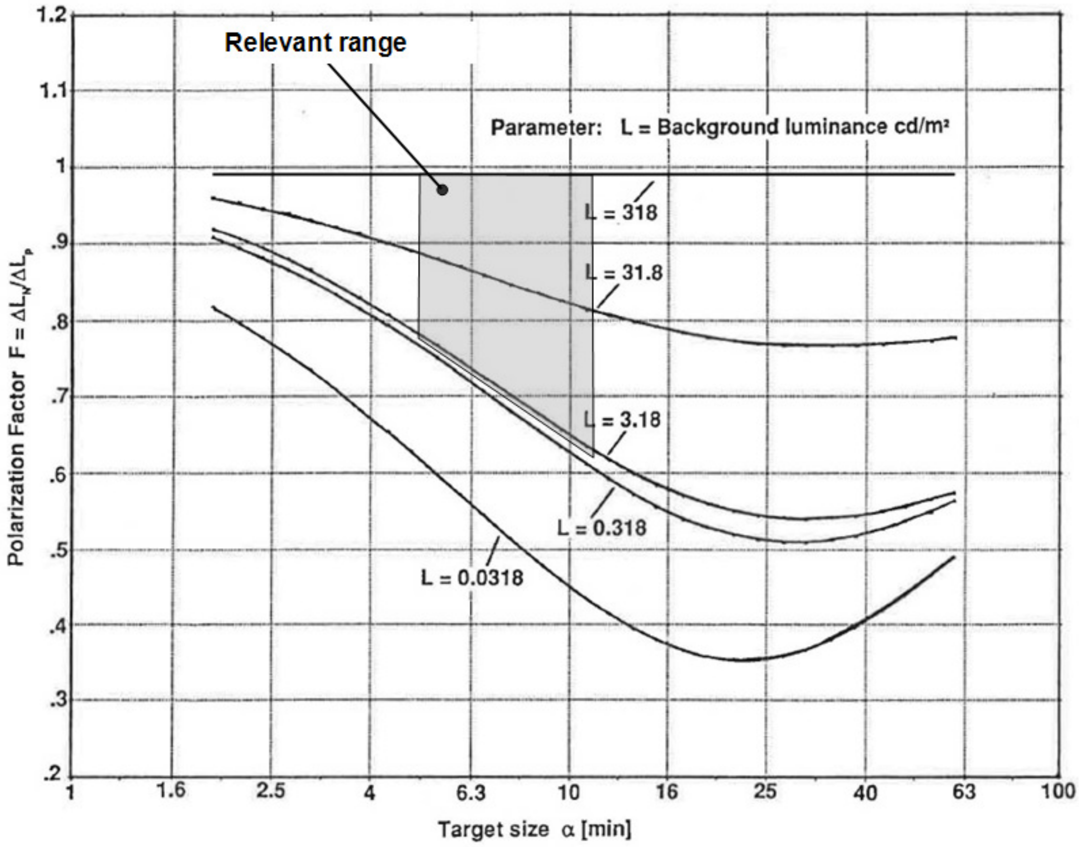


Figure A.11: The polarization factor as a function of the object size and the background luminance.

Figure A.11 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 Visibility 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 sources.

Driving	Visual task				Disability glare			Criteria (minimum)		
Design	Driver	Size	Contrast	Glance	Daylight	Lighting	Other	Visibility	Interior	Time per
speed	age	of object	of object	duration		installation	sources	Level	luminance	factor 10
V					Lseq	D	Lseq	VL	Lin	t10
km/h	23-75 y	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
80	23,0	0,2	-28	0,5	300	0,1	0,25	4,29		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

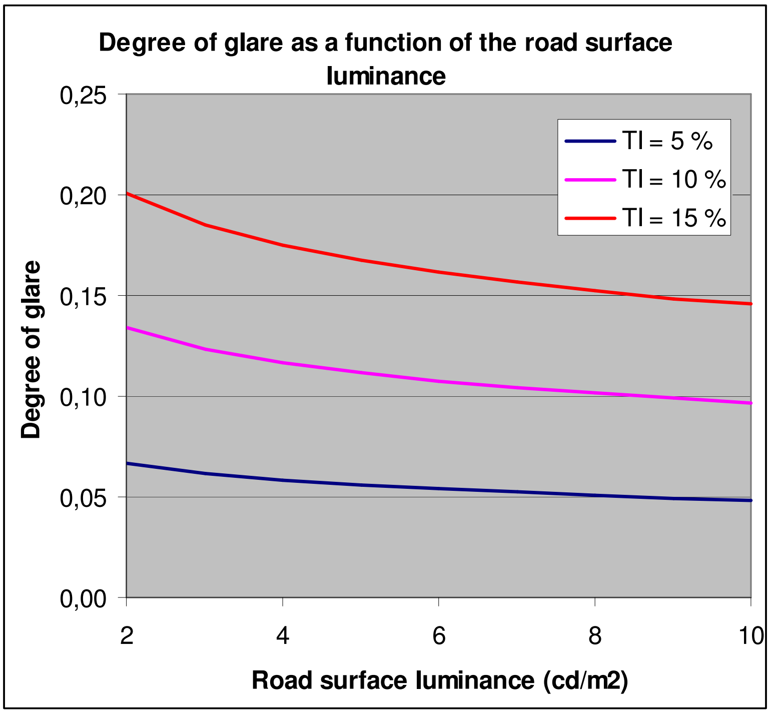
The actual values reflect an average curve for both driving directions in a number of tunnels in Norway. It is pointed out that there are strong deviations from this curve in some of these tunnels.

The degree of glare D applies for the glare caused by the luminaires of the tunnel lighting installation as 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.12 in dependence of the road surface luminance and for the above-mentioned TI values.

Figure A.12: Degree of glare as a function of the road surface luminance.



Judged from figure A.12, 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.2, 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.2 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.2: 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

A.5 Input data for criteria

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

Driving	Visual task				Disability glare			Criteria (minimum)		
Design speed V	Driver age	Size of object	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	23,0	0,2	-28	0,5	300	0,1	0,25	4,29		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 4,29. This is not a handy value, but has some advantage for the examples in annex B.

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 20 % higher than 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	Initial	Interior	VL		VL		Length of	Length of	Time in the	k factor
distance	luminance	luminance	at tunnel entrance		interior zone		threshold	transition	transition	
	Lth	Lin	intended	actual	intended	actual	zone	zone	zone	
m	cd/m2	cd/m2	agreement		agreement		m	m	seconds	
100	197	1,25	4,29	4,29	4,29	4,29	100	226	10,2	0,031

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.

Only the k factor needs to be explained. It is defined in CIE 88:1990 as the ratio between L_{th} and the L_{20} value, which is also defined in CIE 88:1990. Therefore, in order to provide the k factor, it is necessary to determine the L_{20} value.

The L_{20} value, on the other hand, is estimated by means of a correlation between values of and L_{seq} and L_{20} derived for 15 tunnels in Norway measured in both directions. This correlation is shown figure A.13, 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 %.

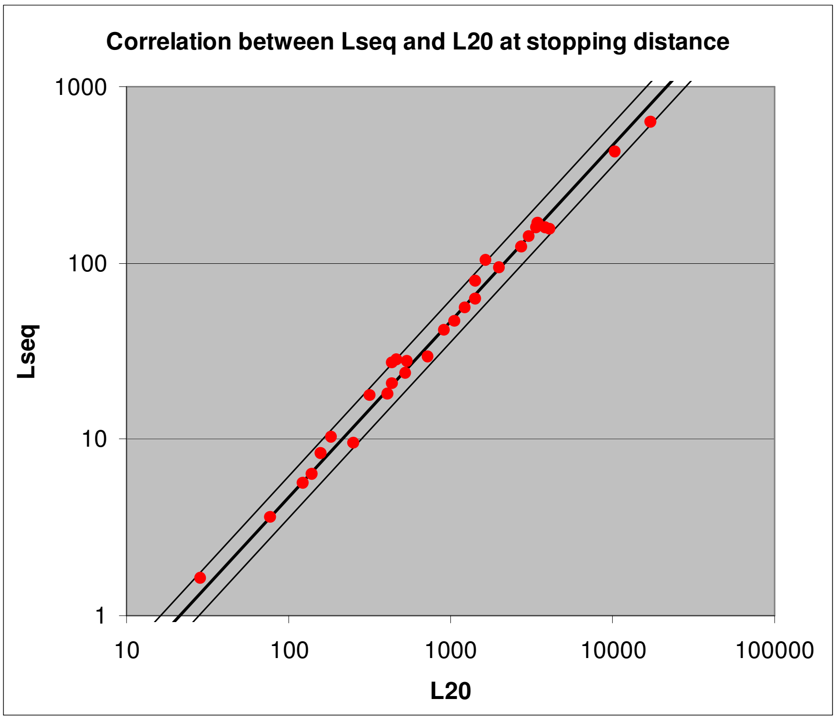


Figure A.13: Correlation between of L_{seq} and L_{20} for 15 tunnels in Norway measured in both directions.

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 drivers age.

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

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, 4 and 5 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.

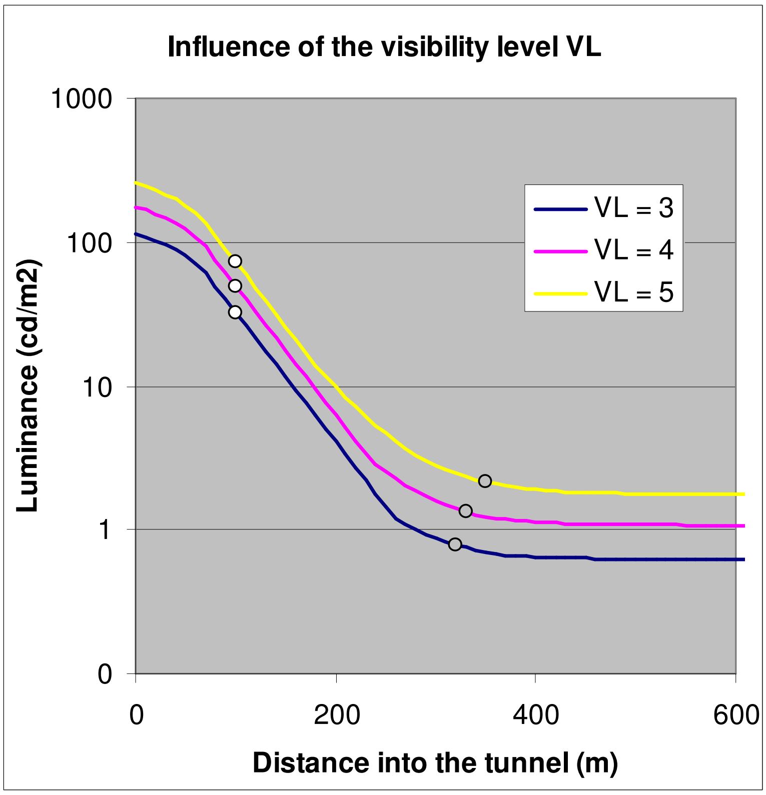


Figure B.1 Luminance profiles for different values of the visibility level VL.

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.

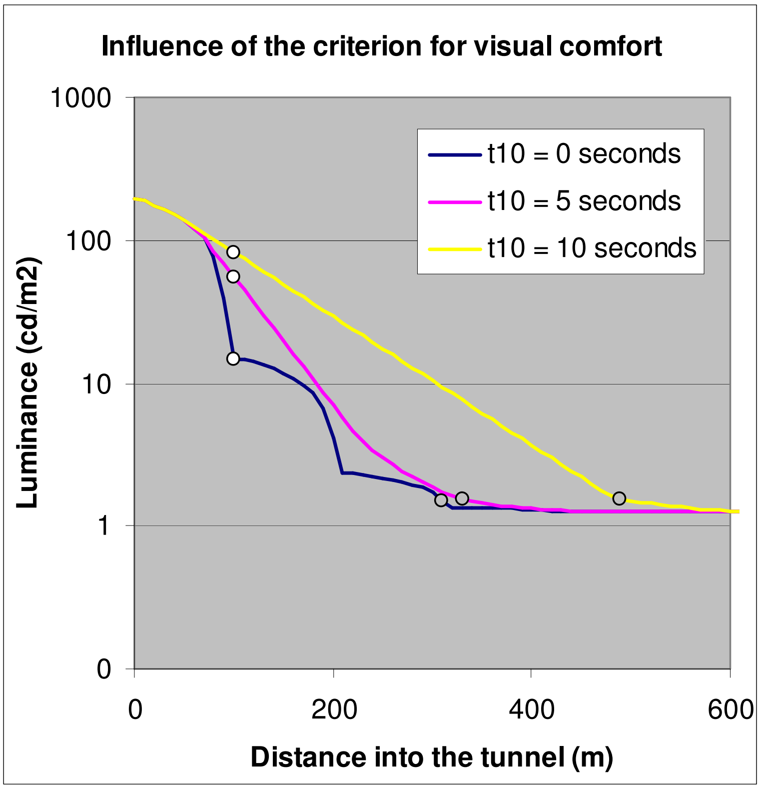
For a value of t_{10} of 10 seconds, the luminance profile is forced to become more wide by the criterion. This leads to a prolongation of the transition zone.

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.



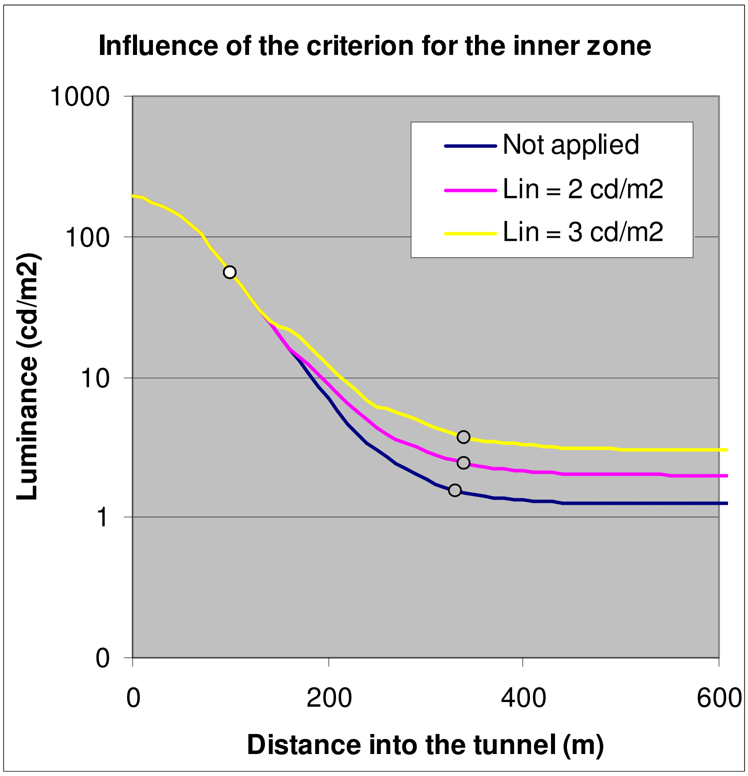
B.2.3 Luminance in the interior zone

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.

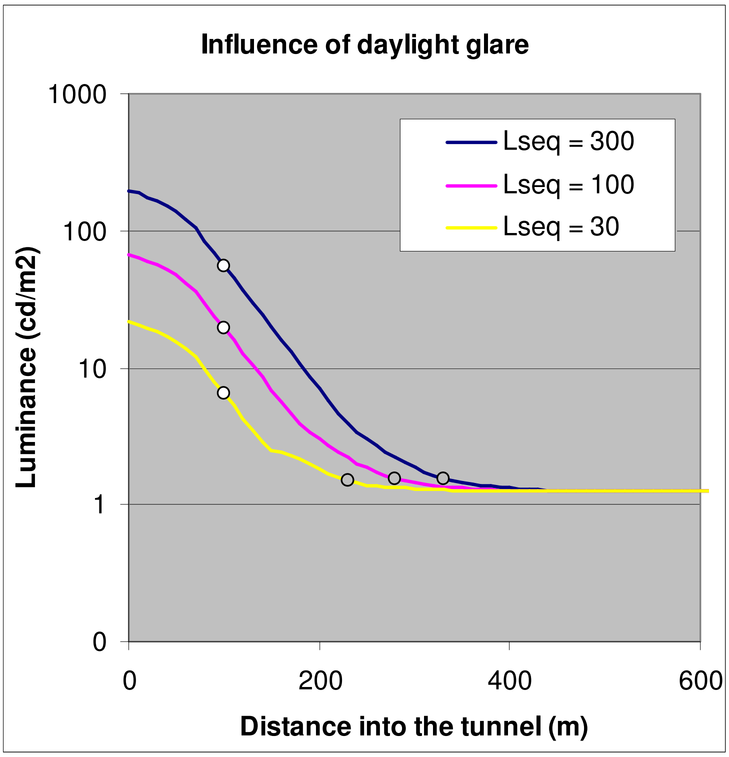


Figure B.4: Luminance profiles for different settings of L_{seq}.

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.

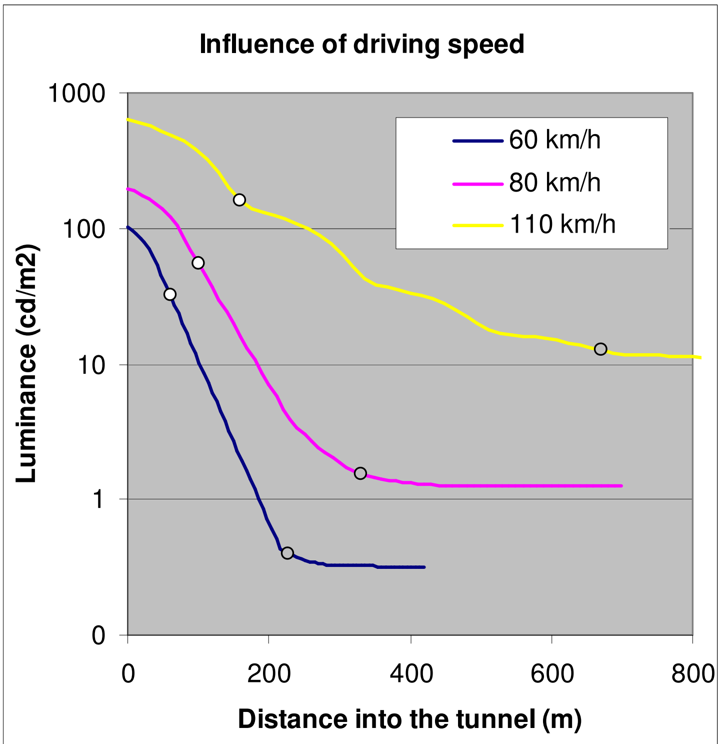


Figure B.5: Luminance profiles for different settings of the driving speed.

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

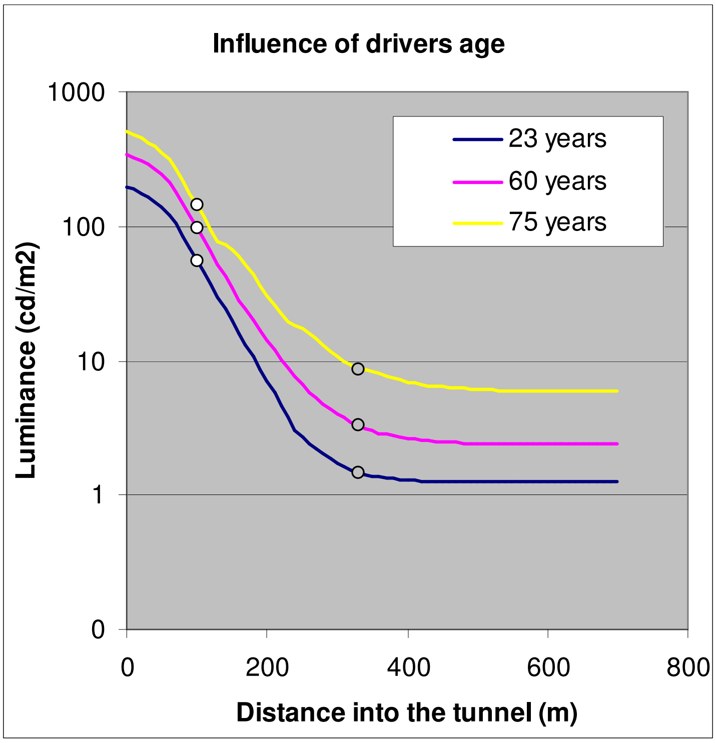


Figure B.6: Luminance profiles for different ages of the driver.

B.4 Comparison to recommendations in CIE 88:1990

B.4.1 The initial luminance in the threshold zone

CIE 88:1990 has the recommendations for the initial luminance in the threshold zone shown in figure B.7.

Figure B.7: CIE 88:1990 recommendations for the initial luminance in the threshold zone.

	Symmetrical lighting system ($L/E_v \lesssim 0,2$)	Counter Beam Lighting system ($L/E_v \gtrsim 0,6$)
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 stopping distances of 60, 100 and 160 m are linked to driving speeds of 60, 80 and 110 km/h. On this basis, the luminance profiles in figure B.8 have been constructed to match the recommendations for a symmetrical lighting system. The match has been obtained by settings of the drivers age as shown in table B.1. The marks on the luminance profiles indicate the ends of the threshold and transition zones.

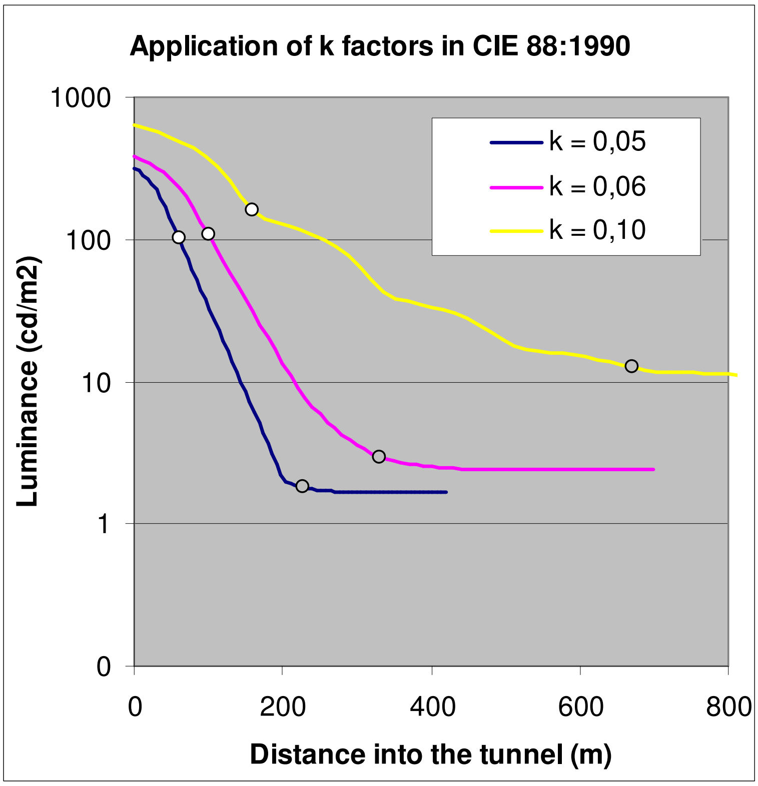


Figure B.8: Luminance profiles matching recommendations for k values in CIE 88:1990.

Table B.1: Settings of drivers age that provide a match to the recommendations in CIE 88:1990.

Intended speed km/h	Stopping distance m	k factor	Driver age years
110	160	0,10	23
80	100	0,06	64
60	60	0,05	83

Whether or not drivers of age are able to cope with the approach to the tunnel depends strongly on the intended speed. At 110 km/h it is a no, at 80 km/h the age is limited to 64 years and at 60 km/h even quite old drivers should be able to cope.

The validity of these statements does of course depend on other input values. But it is clear that a raise of the k factor by a factor of 2 (from 0,05 to 0,10) for speeds from 60 to 110 km/h is insufficient. The excel file predicts that the raise should have been by a higher factor.

However, the recommendations probably reflect what is practically and economically feasible. Further, drivers of age can improve their conditions by driving at a lower speed than the design speed and are assumed to be willing to do that.

The facility of the excel file of a second driver is used to test the effect of a reduced speed by first setting a lower speed and then raising the age until the visibility level is at the preset value.

In the case of an intended speed of 110 km/h, drivers of a high age - 75 years or more - need to reduce their speed to 90 km/h in order to cope.

In the case of an intended speed of 80 km/h, drivers of a high age – 75 years or more – should be able to approach the tunnel, if reducing the speed to 70 km/h.

B.4.2 The luminance in the interior zone

CIE 88:1990 has the recommendations for the luminance in the interior zone L_{in} shown in figure B.9.

Figure B.9: CIE 88: 1990 recommendations for the luminance in the inner zone.

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

The stopping distances of 60, 100 and 160 m are again linked to driving speeds of 60, 80 and 110 km/h. On this basis the luminance profiles in figure B.10 have been constructed to match the recommendations for a medium traffic flow. The match is obtained by the settings the drivers age as shown in table B.2.
The marks on the profiles indicate the ends of the threshold and transition zones.

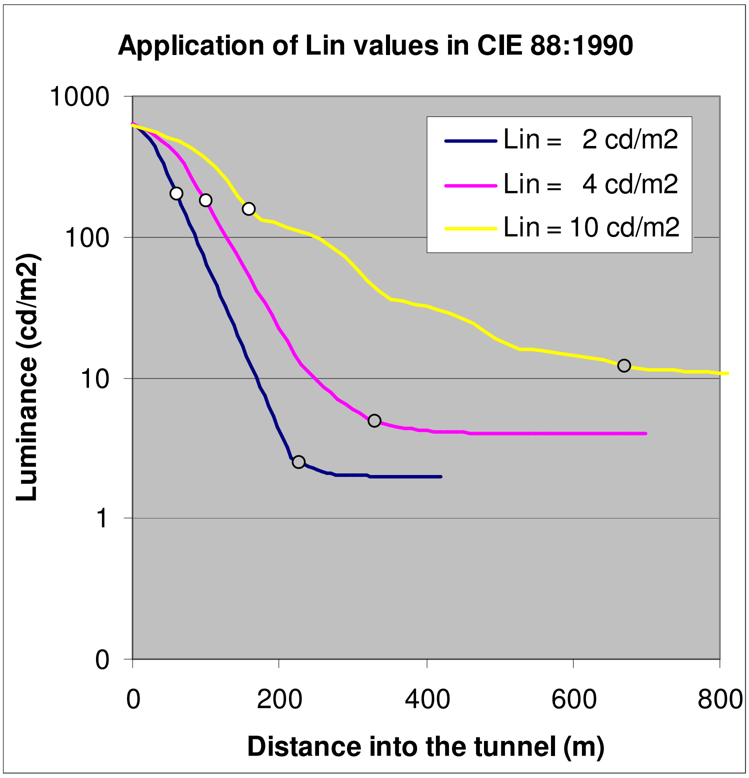


Figure B.10: Luminance profiles matching recommendations for the luminance in the interior zone in CIE 88:1990.

Table B.2: Settings of drivers age that provide a match to the recommendations in CIE 88:1990.

Design speed km/h	Stopping distance m	L_{in} cd/m^2	Driver age years
110	160	10	23
80	100	4	72
60	60	2	87

The comments in B.4.1 apply equally well in this case.

Whether or not drivers of age are able to cope with the conditions in the interior zone depends strongly on the intended speed. At 110 km/h it is a no, at 80 km/h the age is limited to 72 years and at 60 km/h even quite old drivers should be able to cope.

As with the k factors, it is tested what older drivers obtain by reducing their speeds.

In the case of an intended speed of 110 km/h, drivers of a high age - 75 years or more - need to reduce their speed to 90 km/h in order to cope with driving in the interior zone.

In the case of an intended speed of 80 km/h, only a small decrease of speed would help drivers of a high age.

B.4.3 The driving time in the transition zone

CIE 88:1990 defines a luminance profile in the inner zone that involves a driving time of 20 seconds. For comparison, figure B.11 shows the time in the transition zone as a function of the driving speed for two settings of the t_{10} value.

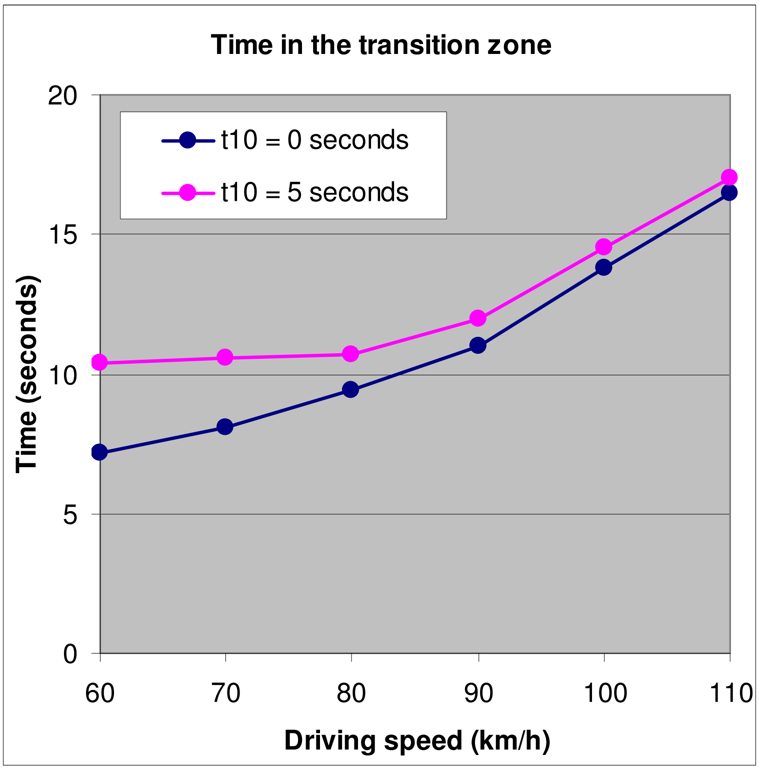


Figure B.11: Time in the transition zone for two settings of the L_{10} value.

Figure B.11 shows 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.11 shows driving times from approximately 11 to 17 seconds as compared to the above-mentioned 20 seconds. Therefore, it should be possible to use shorter transition zones, in particular at the lower driving speeds.