A tool for the 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 work aims at a tool for the analysis of tunnel lighting that is based on visual performance and visual comfort. This tool is an excel file by the name "Analysis of tunnel lighting based on visual performance and visual comfort", which is freely available.

The excel file 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 and may wish to present the excel file the committee.

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

Report

1. A drive simulated by the excel file

The excel file simulates a drive in daylight starting at the reference position a 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 one stopping distance ahead. The road surface luminance at the object is determined in accordance with three criteria and the input data as described in the following. The luminance values form a profile of the road surface luminance.

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 all ten steps, the driver is exposed to glare from the daylight as describe by values of the equivalent veiling luminance L_{seq}. These values are normally gradually decreasing as the driver approaches the tunnel entrance.

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

The criterion is complied with by determining a proper value of the local road surface luminance in each step, when taking the disability glare into account. In the first step at the tunnel entrance, the luminance is called L_{th} and is normally at its highest. In the following steps, the luminance can decrease gradually in step with the L_{seq} values.

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 the details relating to the transverse location of the object and the directionality of lighting into account. However, counter beam lighting at the threshold zone can be taking into account by setting a numerically large, but negative contrast.

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

The road surface luminance can decrease gradually in the transition zone, as discussed in the next section, until it reaches a constant level. This marks the start of the inner zone with a constant road surface luminance L_{in}.

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

A value of L_{in} may be calculated by same method as for the luminance in the threshold zone, 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 like marker lights as well.

The glare from the lighting installation is described by a value of the L_{seq} found 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}.

If L_{in} values are calculated on this basis, the influence of the driving speed in the range from 60 km/h to 110 km/h turns out to cause a variation of the calculated values of L_{in} of a large factor – up 30. Compared to this, the values supplied in CIE 88:1990 varies with the driving speed in this range by a factor of 3 only.

The traditional values cannot be a factor of 10 wrong, so it is concluded that they are based on additional criteria like drivers general orientation and feeling of safety when driving in tunnels.

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 inner zone equal to the input value. 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 a minimum visibility level. The minimum VL is the value derived for the inner zone – when the desired value of L_{in} is set directly – else the minimum VL used for the threshold 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, but has an effect only in the threshold zone as the road surface luminance is constant in the inner zone.

The basis for this 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, and has been included in the excel file. It is used as described below.

In each step, 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 luminance in the previous step times a factor that relates to the t_{10} value. Whenever the luminance calculated on the basis of the VL value is lower than this 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 steps.

5. Input values and results

Input values and results are described in detail in annex A, but summarized below.

Input values include:

a. the driving speed,
b. the driver age,
c. the dimension of the object which is a vertical square placed on the road surface,
d. the contrast of the object to the road surface,
e. the observation time,
f. glare from daylight by means of the equivalent veiling luminance L_{seq} at a stopping distance from the tunnel entrance and also a curve for the gradual decrease of the $_{Lseq}$ when approaching the tunnel entrance,
g. glare from the road lighting installation by means of the degree of glare D,
h. glare from other glare sources, in particular headlamps on opposing vehicles, by means of an L_{seq} value,
i. the minimum VL value,

j. an optional setting of the L_{in} value,
k. the t_{10} value.

The final result is the luminance profile. To this is added a profile of VL values.

Additional results are:

a. the stopping distance for the relevant driving speed,
b. the initial luminance in the threshold zone L_{th},
c. the luminance in the interior zone L_{in},
d. the VL value in the interior zone (deviates from the minimum VL value, when the L_{in} value has been set)
e. the length of the threshold zone (equal to the stopping distance),
f. 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),
g. the duration of driving in the transition zone,
h. the k factor (based on an estimated value of L_{20}).

The results e, f., g. and h. have been added for easy comparison to CIE 88:1990.

Some play with the excel file shows that the luminance values can get extremely high, if one sets several demanding input values, such as a high driving speed with a long stopping distance, a high age of the driver, a low contrast of the object, large levels of disability glare and a high visibility level.

It is suggested to leave the input values b., c., d., e. and i. as they are preset in the excel file. After all, these input values are rather arbitrary, except that they together form a general measure of the visibility conditions.

6. Examples of calculations

Some examples of calculations are presented in annex B.

These examples include the influences of the criteria for visual performance and visual comfort.

The examples also include the threshold luminance L_{th} and the luminance in the interior zone L_{in}. It is shown that these values are influenced by the driving speed to a stronger degree than reflected by the recommendations in CIE 88:1990. Both values are smaller than the values indicated in CIE 88:1990 at the lowest driving speed of 60 km/h, but gradually approach those of CIE 88:1990 with increasing driving speeds and match them at the highest driving speed of 110 km/h.

Additionally, the examples include the luminance profile in the transition zone. It is shown that the luminance profile depends strongly on both the driving speed and the degree of glare D. These profiles lie below the single profile for the transition zone offered in CIE 88:1990, except for a few cases with the highest driving speed of 110 km/h.

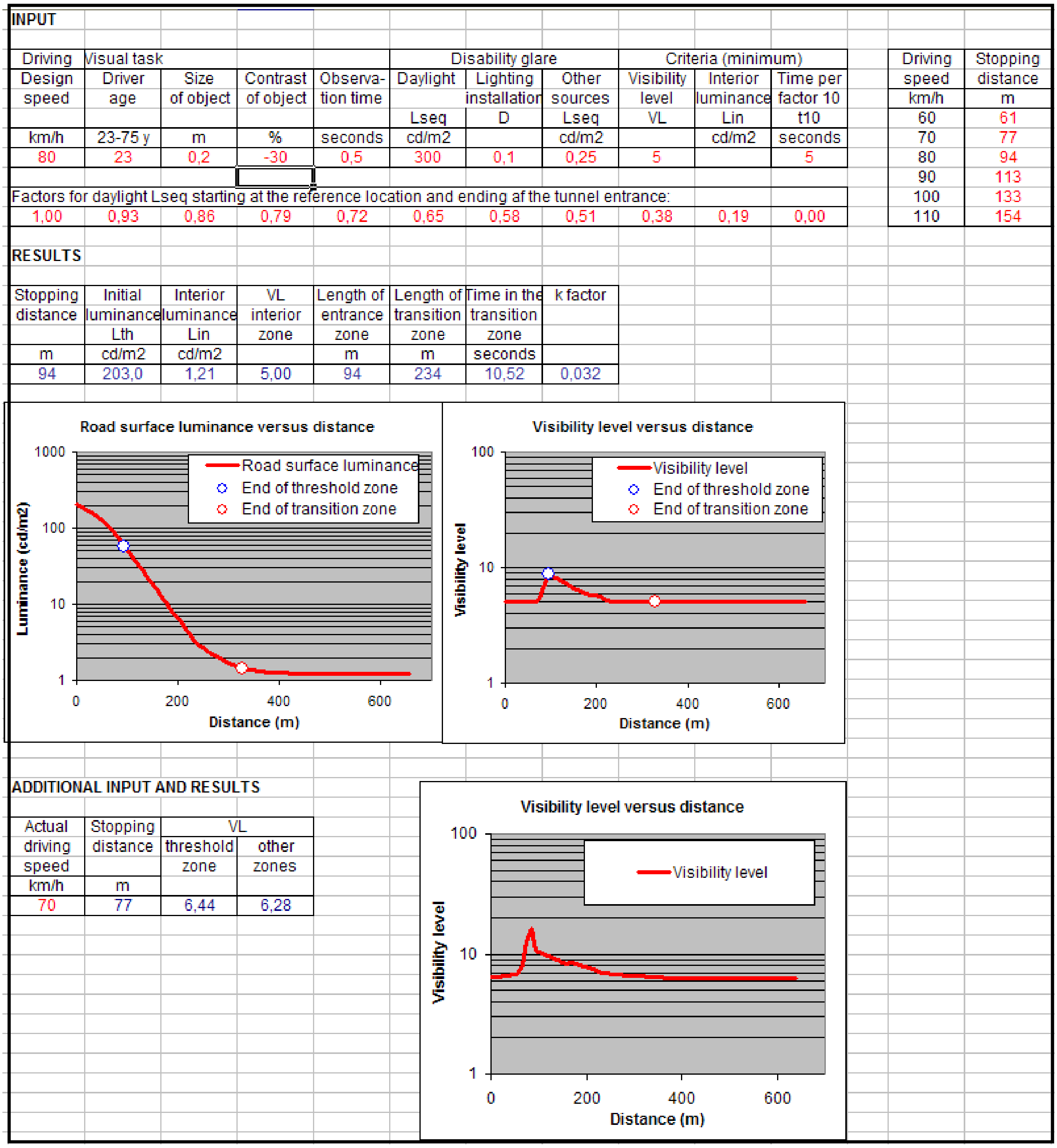
Note: The authors are of course aware of CIE 88:2004, but prefer to compare to the older version for a number of reasons. CIE 88:1990 is probably still the basis for national tunnel lighting standards in many countries, it covers much of CIE 88:2004, and it is more simple to relate to.

Finally, some examples show that a driver improves his visibility conditions fairly strongly by driving at a lower speed than the design driving speed.

Annex A: Input and results

A.1 The user part of the excel file

The user part of the excel file is found in the sheet labelled “Input and results” and is shown in figure A.1. The values in red font are input values, and only these should be modified. Whenever input data are modified, the results and the curves in the diagrams change accordingly,



INPUT

Driving	Visual task				Disability glare			Criteria (minimum)		
Design speed	Driver age	Size of object	Contrast of object	Observa-tion time	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	0,2	-30	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	0,93	0,86	0,79	0,72	0,65	0,58	0,51	0,38	0,19	0,00

Driving speed km/h	Stopping distance m
60	61
70	77
80	94
90	113
100	133
110	154

RESULTS

Stopping distance	Initial luminance Lth	Interior luminance Lin	VL interior zone	Length of entrance zone	Length of transition zone	Time in the transition zone	k factor
m	cd/m2	cd/m2		m	m	seconds	
94	203,0	1,21	5,00	94	234	10,52	0,032

ADDITIONAL INPUT AND RESULTS

Actual driving speed	Stopping distance	VL	
		threshold zone	other zones
km/h	m		
70	77	6,44	6,28

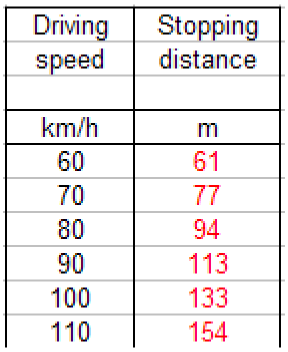
Figure A.1: User part of the excel file.

The results include an additional table with the luminance and visibility levels profiles, which can be copied into other excel files for the purpose of producing diagrams. This table is found in the sheet labelled “Table”.

A.2 Input of the design driving speed and the stopping distance

The first input is the design driving speed to be given as one of the values in the small table in the upper right part of figure A.1. The excel file then picks the corresponding value in the table for the stopping distance. This table is also shown in table A.1.

Table A.1: Stopping distances.



Driving speed	Stopping distance
km/h	m
60	61
70	77
80	94
90	113
100	133
110	154

A.3 Input data for the visual task

The next input group of input data 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 duration of a glance on the object called the observation time,

The need for luminance increases with age as indicated by an age factor AF shown in figure A.2.

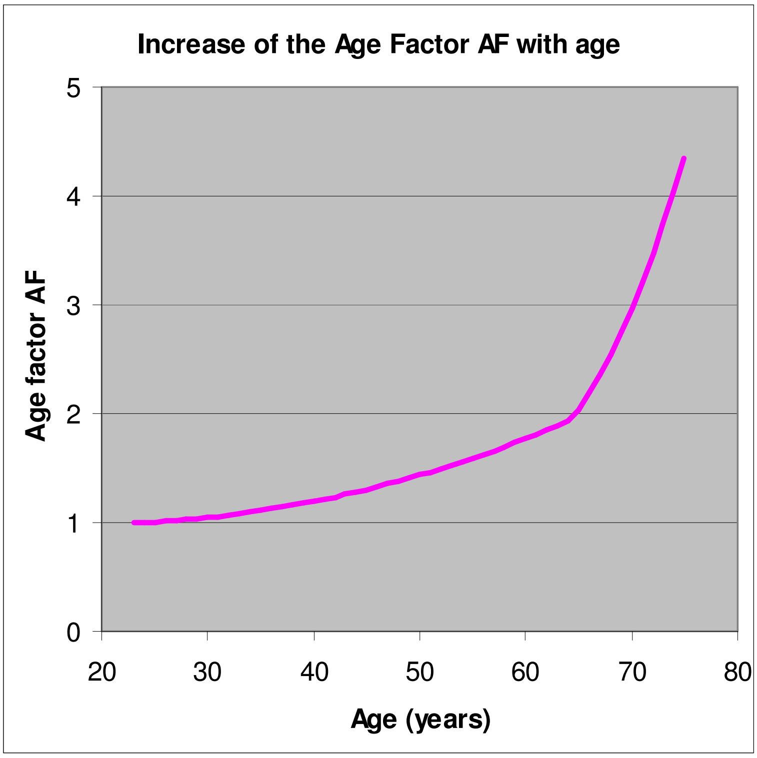


Figure A.2: Increase of the age factor AF with age.

As the factor value goes up to 4,5 for the highest age of 75 years covered by the figure. The luminance level needed to compensate for that goes to the sky as if a person of that age is strongly visually impaired. This is probably not true, as a sizeable fraction of drivers are of age and perform well. Cataracts is a common decease and does cause visual impairment, but is cured in a simple operation.

It is suggested to keep this input value at an age of 23 years.

The size of the object is set to 0,2 m^2, which is the size normally assumed in studies of visibility.

Internally in the excel file, the object is replaced with a circle with same area as the square object. In this case, the diameter is 0,2257 m. The object size is then described by the diameter in minutes of arc as seen at the stopping distance. As the stopping distance ranges from 61 to 154 m, the object size ranges from 12,7 down to 5 minutes of arc.

The contrast of the object is set to -30 %. The negative value reflects that objects are mostly seen in negative contrast against a road surface. Counter beam lighting can be described by a lower value, for instance -50 %.

Internally in the excel file, the visibility level is first calculated as if the contrast is positive. If the contrast is positive, no correction is applied. If, on the other hand, the contrast is negative, a “polarization factor” is applied. The value of this polarization factor depends on the object size and the background luminance as illustrated in figure A.3.

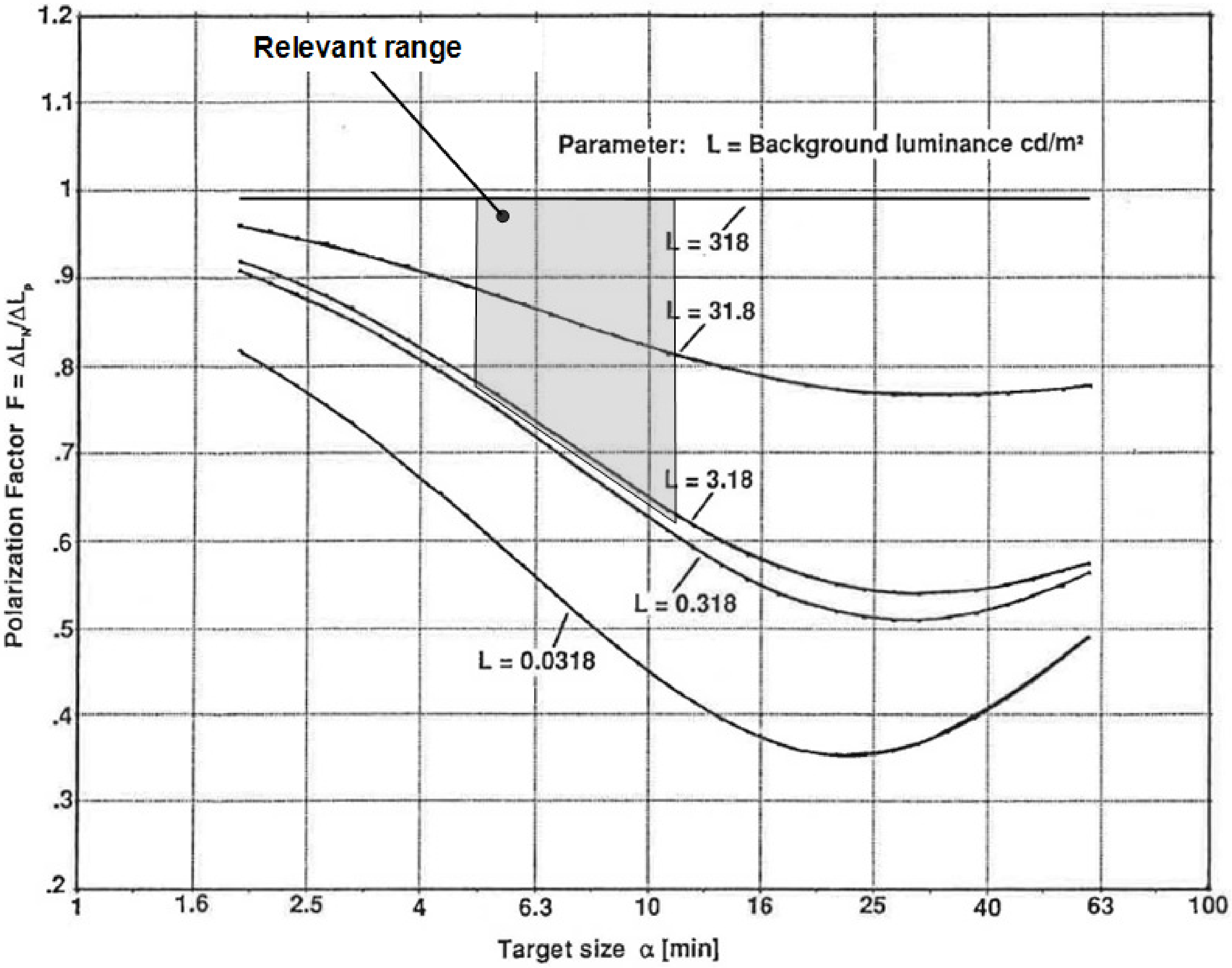


Figure A.3: The polarization factor as a function of the object size and the background luminance.

Figure A.3 is a copy of a diagram in “Visibility of Targets” by Werner Adrian, to which the range that is relevant for tunnel lighting has been added. It can be seen that the factor is close to 1 for high luminance levels relevant for the threshold zone, but significantly lower for low luminance levels relevant for the interior zone. Additionally, the lowest values are for large object sizes corresponding to low driving speeds.

The visibility level is in inverse proportion to the value of this factor. Therefore, 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 observation time is described by a factor to the visibility level, which has a value of 1 at 2 seconds, but decreases with decreasing observation time.

The value is set 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 Input data for glare

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

- glare caused by daylight at the location of the driver one stopping distance from the tunnel entrance portal,
- the degree of glare caused by the lighting installation,
- additional glare caused by other glare sources.

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 as should be 1,00, while the last is for the location at the tunnel entrance portal and should be 0,00. 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.

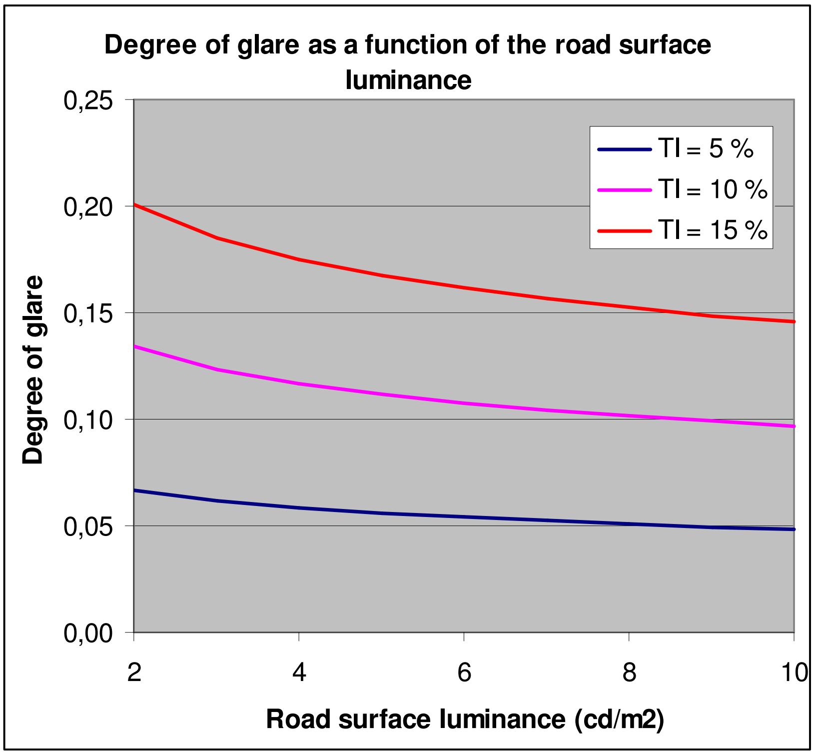
The actual values shown in figure A.1 reflect an average curve for both driving directions in 15 tunnels in Norway. It is pointed out that there are strong deviations from this curve in some of these tunnels.

The degree of glare D applies for the glare caused by the luminaires of the lighting installation. D is the ratio between the L_{seq} value and the road surface luminance, and is assumed to be constant over the length of the tunnel.

The 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 in this case.

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 $L_{seq}/L = TI/(65 \times L^{0,2})$. Such values are shown in figure A.4 in dependence of the road surface luminance and for the above-mentioned TI values.

Figure A.4: Degree of glare as a function of the road surface luminance.



Judged from figure A.4, 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.

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 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 luminance.

VL is the visibility level and concerns 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 with more than one task to perform can detect objects.

L_{in} is the luminance in the interior zone. If the input field is left blank, the above-mentioned VL criterion is used 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 and the inner zone.

The last criterion concerns visual comfort and is the minimum time measured in seconds for a decrease of the luminance by a factor 10, t_{10}. Values of 2, 3 and 5 seconds seem to be relevant, but even higher values could be considered.

A.6 Results of calculations

The final result is the set of luminance values, which may be called the luminance profile. To this is added a profile of VL values. These profiles are shown in diagrams, refer to figure A.1.

Additional results are:

i. the stopping distance for the relevant driving speed,
j. the initial luminance in the threshold zone L_{th},
k. the luminance in the interior zone L_{in},
l. the VL value in the interior zone (deviates from the minimum VL value, when the L_{in} value has been set)
m. the length of the threshold zone (equal to the stopping distance),
n. 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),
o. the duration of driving in the transition zone,
p. the k factor (based on an estimated value of L_{20}).

The results e, f., g. and h. have been added for easy comparison to CIE 88:1990.

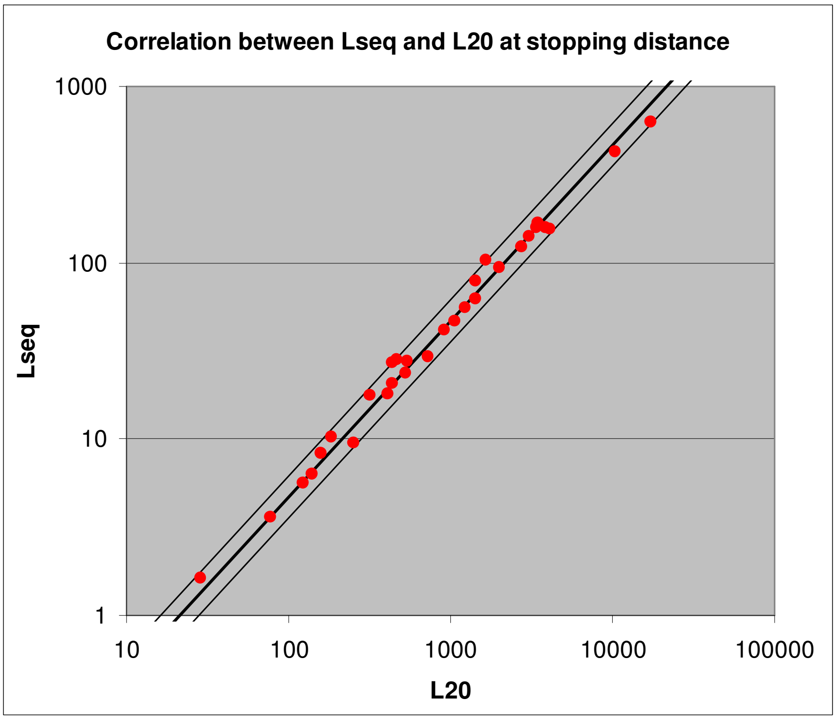
The k factor is the ratio between L_{th} and the L_{20} value defined in CIE 88:1990. The L_{20} value is estimated by means of the correlation between values of L_{20} and L_{seq} shown in figure A.4 for 15 tunnels in Norway measured in both directions.

The regression line in the figure represents 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 %.

The results include a table with the luminance and the visibility level as functions of both the distance and the driving time. This table is found in the sheet labelled “Table”, it can be copied into other excel files for the purpose of producing diagrams.

Figure A.4: Correlation between of L_{seq} and L_{20} for 15 tunnels in Norway measured in both directions.



A.7 Additional input and results

The input value of the driving speed illustrated in figure A.1 is the “design driving speed” that – together with other input values - determines the output values including the profiles of luminance and visibility level shown in diagrams.

Additional input and results include a small table and an additional diagram. The table has only one input value, which is the “actual driving speed”. The results include the stopping distance at this driving speed and visibility levels at the threshold zone and in the interior zone. Additionally, the profile of the visibility level is shown in a diagram.

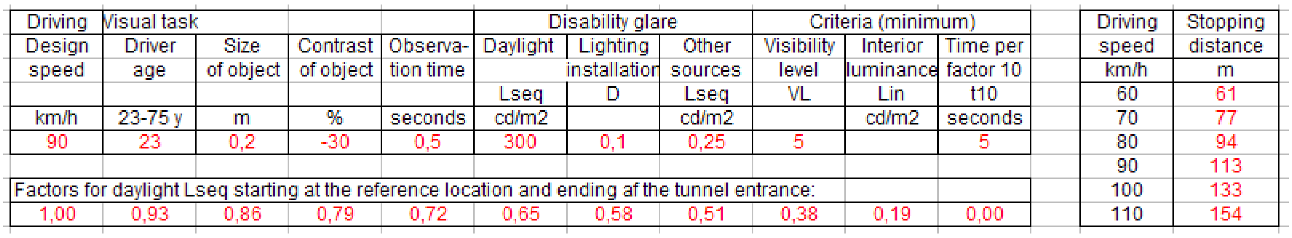
When the two driving speeds are equal, the results agree with the results provided above. However, when the actual driving speed differs from the design driving speed, the results are different and reflect the visibility level experienced by a driver at the actual driving speed.

Annex B: Examples of calculation results

B.1 Introduction

This annex accounts for results of use of the excel file.

The input values are those shown in figure B.1 are used, except when alternative values are clearly stated.



Driving	Visual task				Disability glare			Criteria (minimum)		
Design speed	Driver age	Size of object	Contrast of object	Observa-tion time	Daylight	Lighting installation	Other sources	Visibility level	Interior luminance	Time per factor 10
					Lseq	D	Lseq	VL	Lin	t10
km/h	23-75 y	m	%	seconds	cd/m2		cd/m2		cd/m2	seconds
90	23	0,2	-30	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	0,93	0,86	0,79	0,72	0,65	0,58	0,51	0,38	0,19	0,00

Driving speed	Stopping distance
km/h	m
60	61
70	77
80	94
90	113
100	133
110	154

Figure B.1: Input data

The influences of the criteria for visual performance and visual comfort are considered in sections B.2 and B.3 respectively.

After this follows accounts for the luminance needed at the tunnel threshold L_{th}, the luminance profile in the threshold zone, the luminance levels in the interior zone L_{in} and the luminance profíle in the transition zone in sections B.4, B.5, B.6 and B.7 respectively.

In the last-mentioned sections comparisons are made to recommendations in CIE 88:1990. The results and the recommendations are similar, but deviates from each other in some respects. In particular, the excel file points to a stronger influence of the driving speed/stopping distance for all of the above-mentioned aspects. There is also pointed to a strong influence of the disability glare caused by the luminaires of the lighting installation.

To this is added an account of the influence of the actual driving speed in section B.8. This account also shows a strong influence of the driving speed.

B.2 Influence of the criterion for visual performance

Figure B.2 shows the luminance profiles provided by the excel file for the case that the visual comfort criterion is not applied. This is done by setting the minimum time for a decrease of the luminance, t_{10} to 0 seconds. The profiles stop, where the inner zone is met, so that the values of L_{in} and the total lengths from the tunnel entrance to the inner zone appear in the figure.

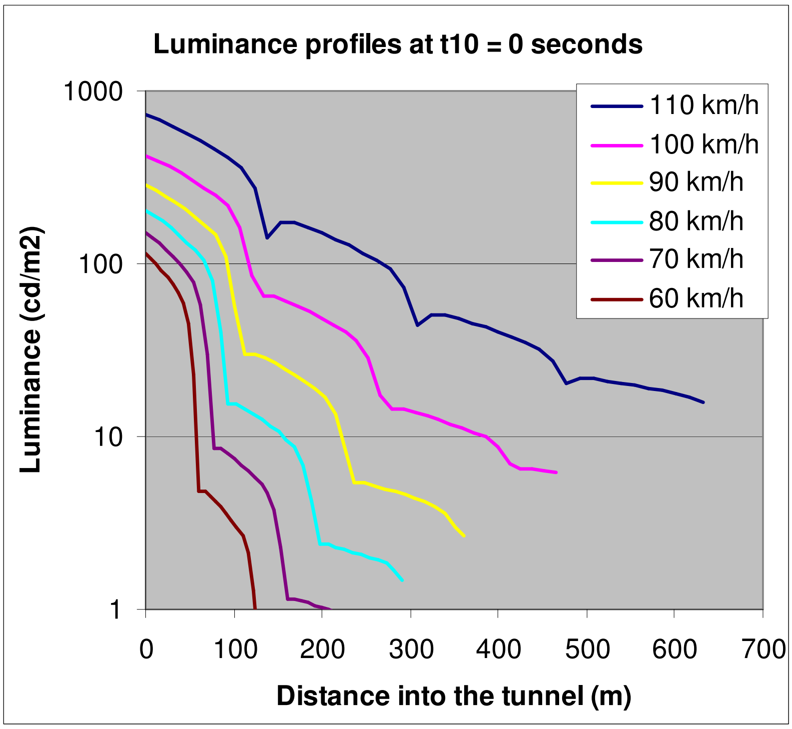
Figure B.2 shows that the value of L_{th} increases quite strongly with the driving speed, from 116 cd/m^2 for the lowest driving speed of 60 km/h up to 726 cd/m^2 for the highest driving speed of 110 km/h.

The value of L_{in} also increases strongly with the driving speed, from 0,41 cd/m^2 to 12 cd/m^2. The same applies for the total length from the tunnel entrance to the inner zone, the range is from 185 m to 676 m.

These matters illustrate that the driving speed is a very strong factor.

The main reason is that the object is to be visible at the stopping distance that is associated with the driving speed. At a high driving speeds, the stopping distance is long, so that the apparent size of the object is small, which leads to compensation in terms of higher luminance. For the total lengths from the tunnel entrance to the inner zone, the stopping distance is in itself an additional factor.

Figure B.2: Luminance profiles determined on basis of the visual performance criterion only.



B.3 Influence of the criterion for visual comfort

Figure B.2 presented in section B.2 illustrates that the pattern of luminance in the threshold zone is repeated in the transition zone for each stopping distance, like echoes. This is interesting, but easily explained by the way that the excel file works.

Figure B.2 was actually made to illustrate this feature, and to provide information on results provided by the criterion for visual performance only.

Figure B.3 shows the luminance profiles after changing the value of t_{10} from 0 to 5 seconds, while figure B.4. shows the luminance profiles after changing the value of t_{10} to 10 seconds.

It is noted that the values of L_{th} and L_{in} remain the same.

For a value of t_{10} of 5 seconds in figure B.3, the luminance profiles become more smooth, but with little overall change of the luminance profiles as compared to figure B.2. On one hand, the criterion prevents any local steep slope. On the other hand, the luminance profiles are not much affected in an overall manner as their slopes are already less steep than set by the criterion over most of their lengths.

For a value of t_{10} of 10 seconds in figure B.3, the luminance profiles for the low driving speeds are forced by the criterion to become more wide. For 60 km/h in particular, the total decrease from L_{th} to L_{in} is by a factor of 100, which must take minimum 20 seconds corresponding to 333 m of driving. The profile for 110 km/h is, on the other hand, not affected by much.

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.3: Luminance profiles for t_{10} = 5 seconds.

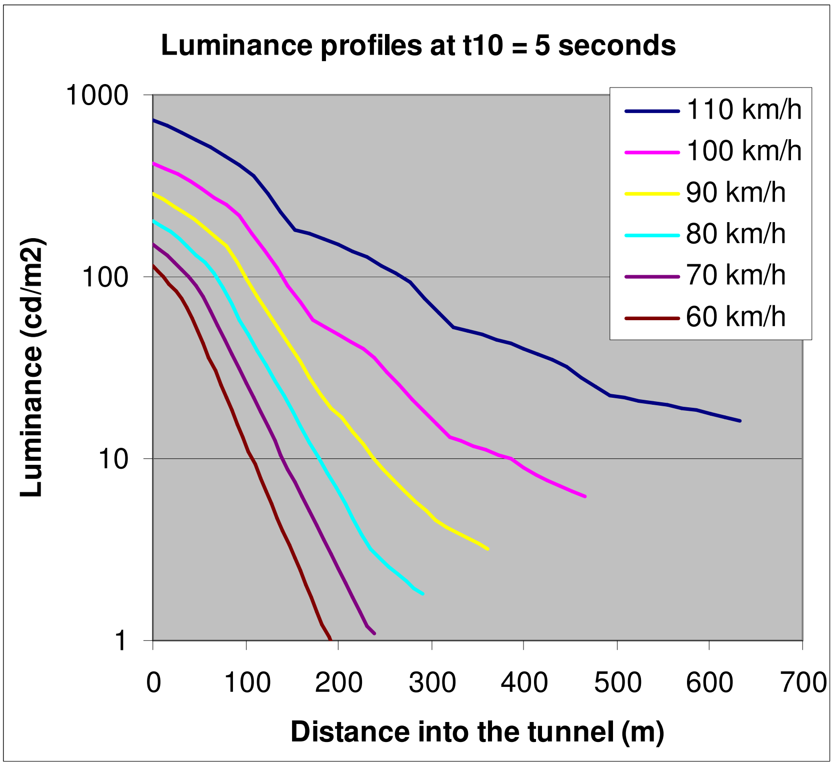
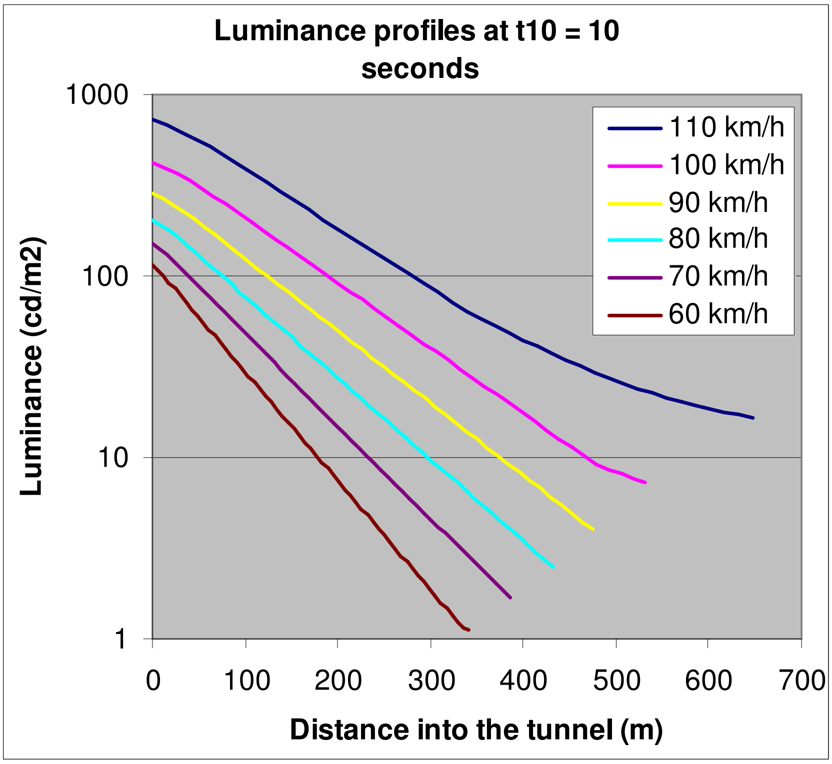


Figure B.4: Luminance profiles for t_{10} = 10 seconds.



B.4 The luminance at the tunnel entrance L_{th}

Figure B.5 shows that the luminance needed at the tunnel entrance, L_{th} is a linear function of the value of L_{seq} caused by daylight at the reference position.

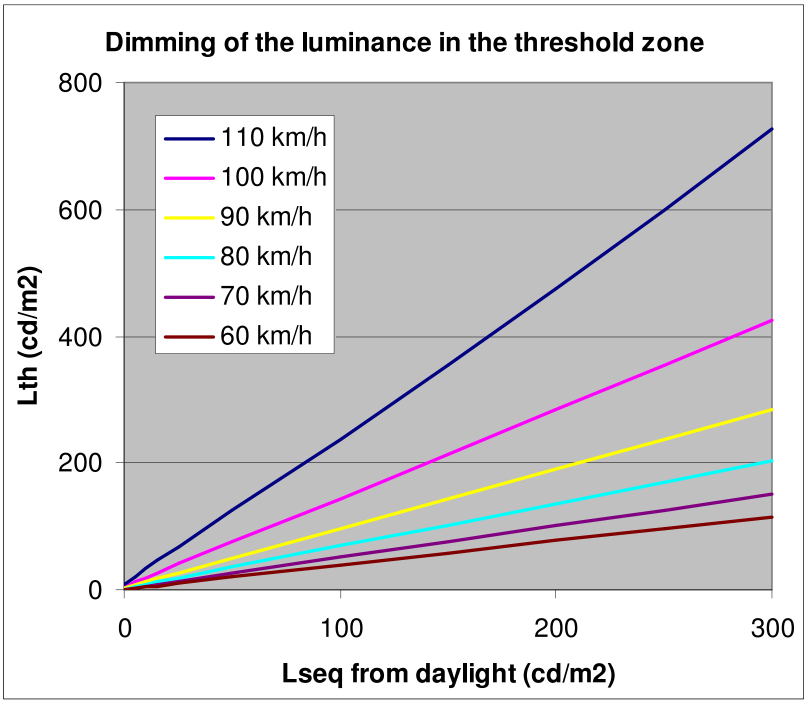


Figure B.5: L_{th} as a function of L_{seq} from daylight.

The lines do not pass quite through the origin, but for most of the range of L_{seq} values, L_{th} is to a good approximation proportional to L_{seq}.

The excel file supplies a value of the k factor as defined in CIE 88:1990. Figure B.6 gives a comparison of these factors to the k factors provided for a few driving speeds in CIE 88:1990.

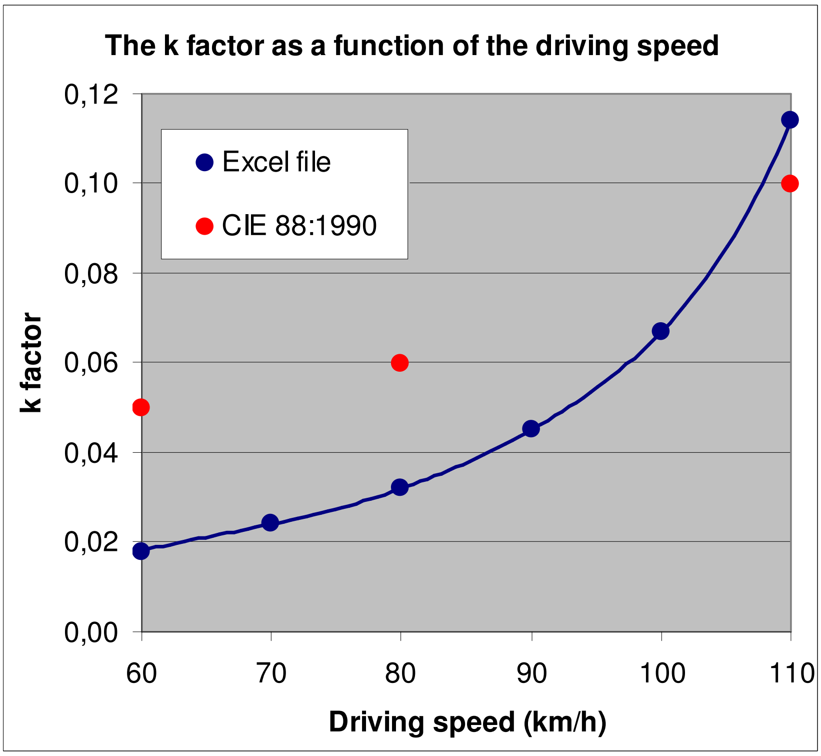


Figure B.6: The k factor as a function of the driving speed.

The excel file predicts that the k factors can be smaller than the values of CIE 88:1990 for the driving speeds of 60 and 80 km/h, while the match is good for the driving speed of 110 km/h.

B.5 The luminance profiles in the threshold zone

Figure B.7 shows luminance profiles in the threshold zone, where both the distance into the threshold zone and the luminance is given in percent.

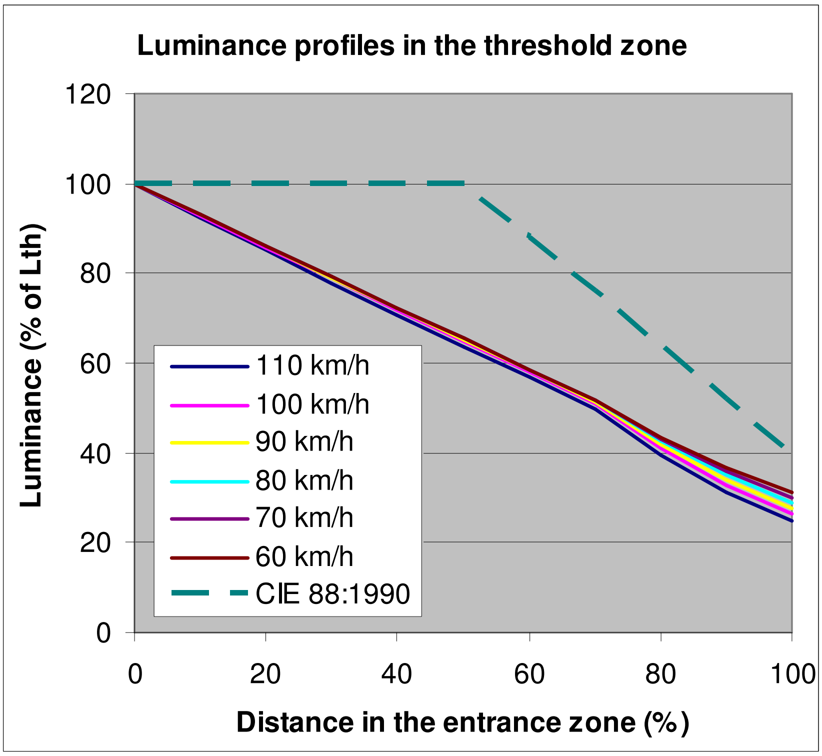


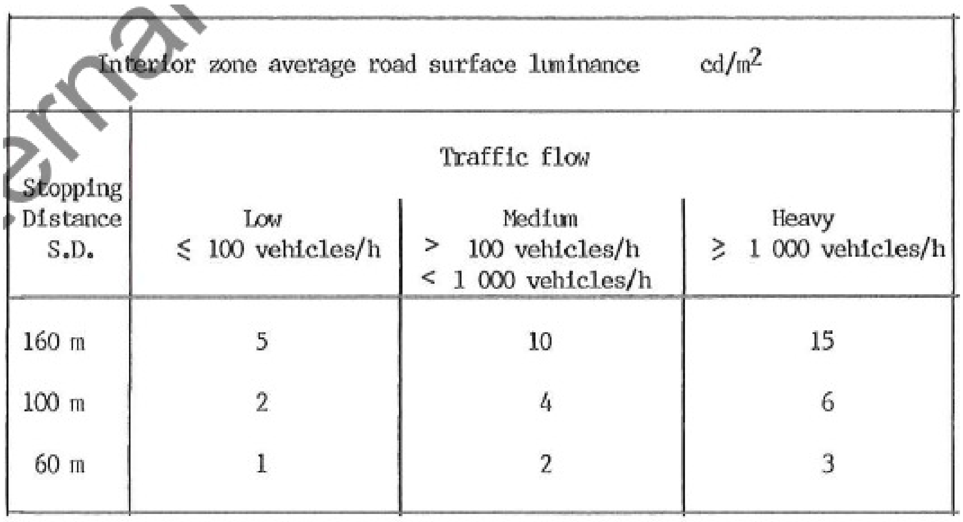
Figure B.7: Luminance profiles in the threshold zone.

The luminance profiles generated by the excel file for the different driving speeds are close to being lines that nearly coincide in figure B.7. This is assumed to be a coincidence created by the input data and the two criteria.

The profile in accordance with CIE 88:1990 is included in figure B.7. It is different by being flat half of the way, and then quickly dropping to 40 % the rest of the way.

B.7 The luminance levels in the interior zone; L_{in}

CIE 88:1990 provides a table of luminance levels in the interior zone for stopping distances of 60, 100 and 160 m and conditions of low, medium and heavy traffic. See figure B.8.



Interior zone average road surface luminance cd/m²			
Stopping Distance S.D.	Traffic flow		
	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 table of luminance levels in the interior zone.

These values are shown in figure B.9 together with a set of values derived with the excel file for a visibility level of 5 in all zones.

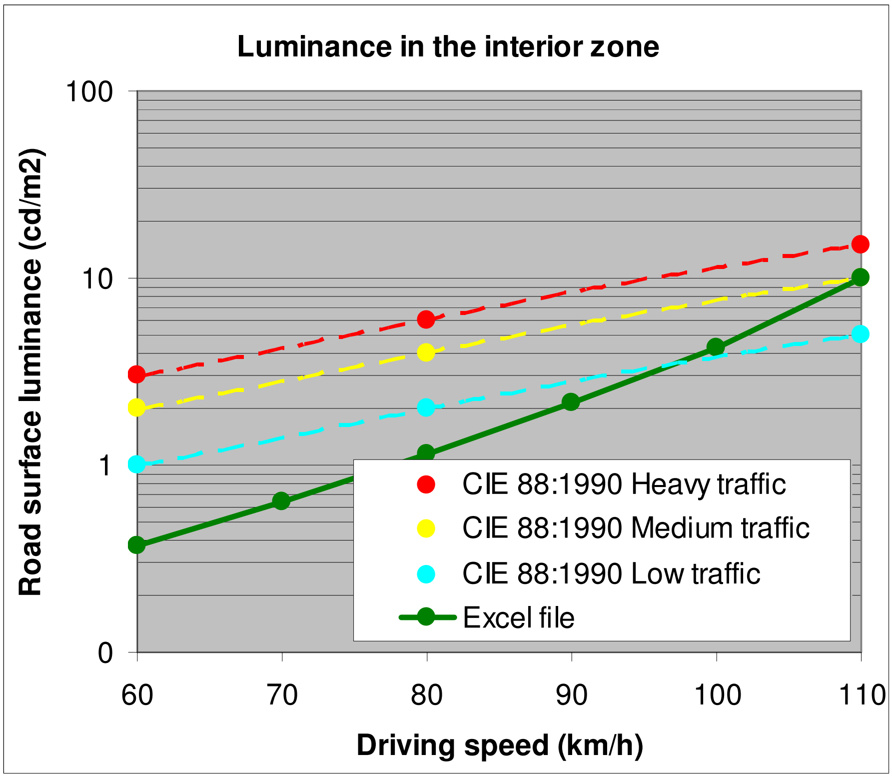


Figure B.9: The luminance in the interior zone.

The two sets of values do not match well. Further, they cannot be brought to match well as the CIE 88:1990 values cover a range of only a factor of three with the driving speed, compared to the range of a factor of approximately 30 covered by the curve generated by the excel file.

Note: CIE 88:2004 also provides values of L_{in} like those in figure B.8. These values cover a range of only approximately 2,5 with the driving speed.

It is concluded that luminance levels used in the inner zone of tunnels cannot be explained by the need for visual performance alone. There must be other criteria in use, like drivers general orientation and feeling of safety.

This is the reason that the road surface luminance in the inner zone L_{in} can be set directly as an input to the excel file. An example of this is shown in figure B.10.

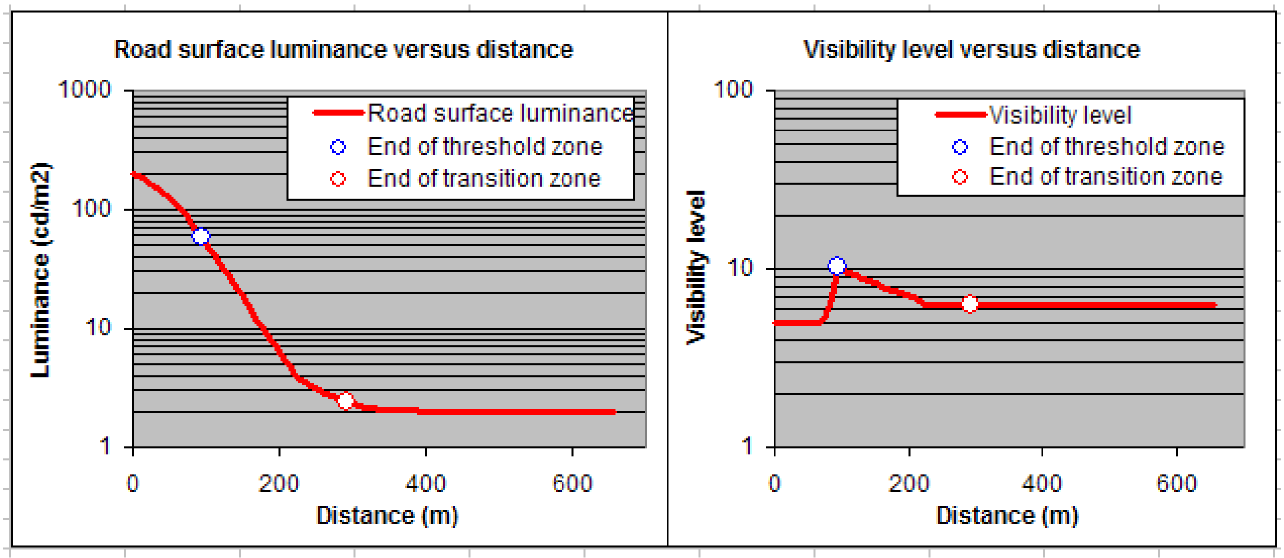


Figure B.10: Example where L_{in} has been set directly to 2 cd/m^2.

B.6 The luminance profíles in the transition zone

Figures B.11, B.12 and B.13 show luminance profiles in the transition zone, where the distance into the zone is replaced by the driving time and the luminance is given in percent of the L_{th} value. The figures apply for a visibility level of 5 in all zones and degree of glare D of respectively 0,05; 0,10 and 0,15.

The profiles are shown only up to the where the inner zone is met for the different driving speeds. This is in order to provide an impression of the time it takes to pass through the transition zone. The actual time periods are shown in table B.1.

Table B.1: Time to pass through the transition zone in seconds.

Degree of glare D	Driving speed					
	60 km/h	70 km/h	80 km/h	90 km/h	100 km/h	110 km/h
0,05	9,6	9,4	9,5	9,7	10,3	12,1
0,10	9,4	10,5	10,5	11,5	14,1	17,3
0,15	11,1	11,0	11,8	14,0	16,9	21,6

Figure B.11: Luminance profiles in the transition zone for a degree of glare D equal to 0,05.

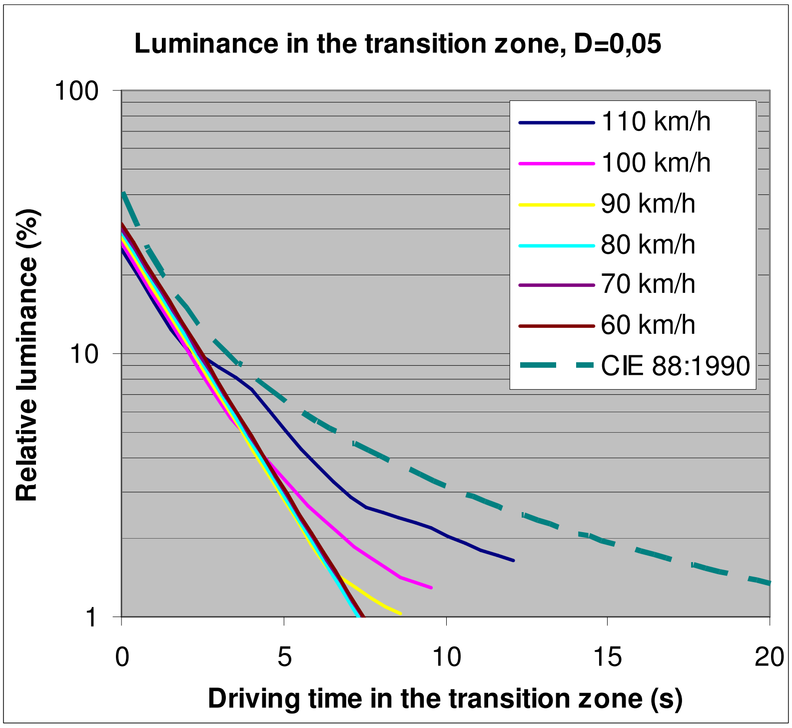


Figure B.12: Luminance profiles in the transition zone for a degree of glare D equal to 0,10.

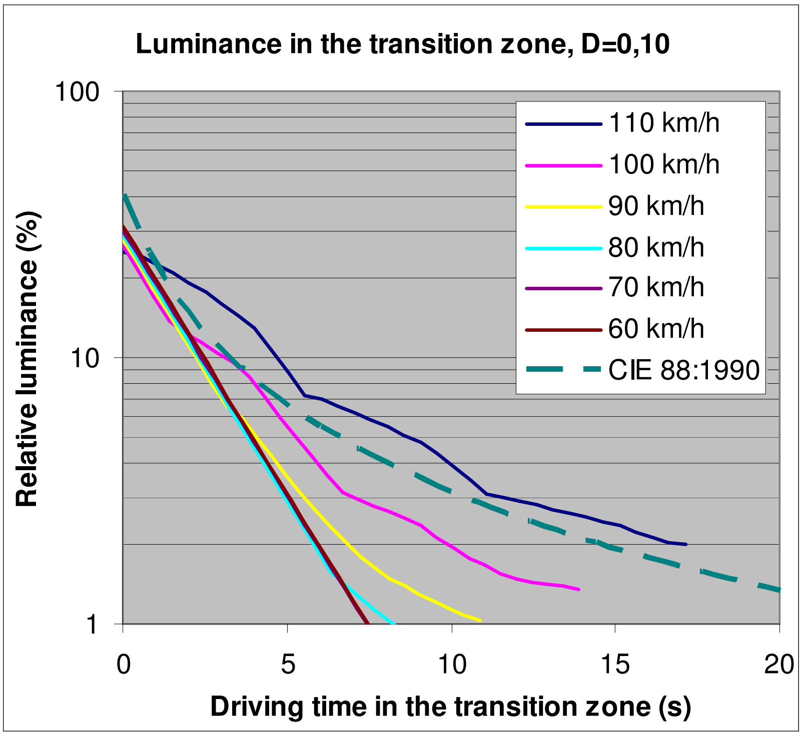
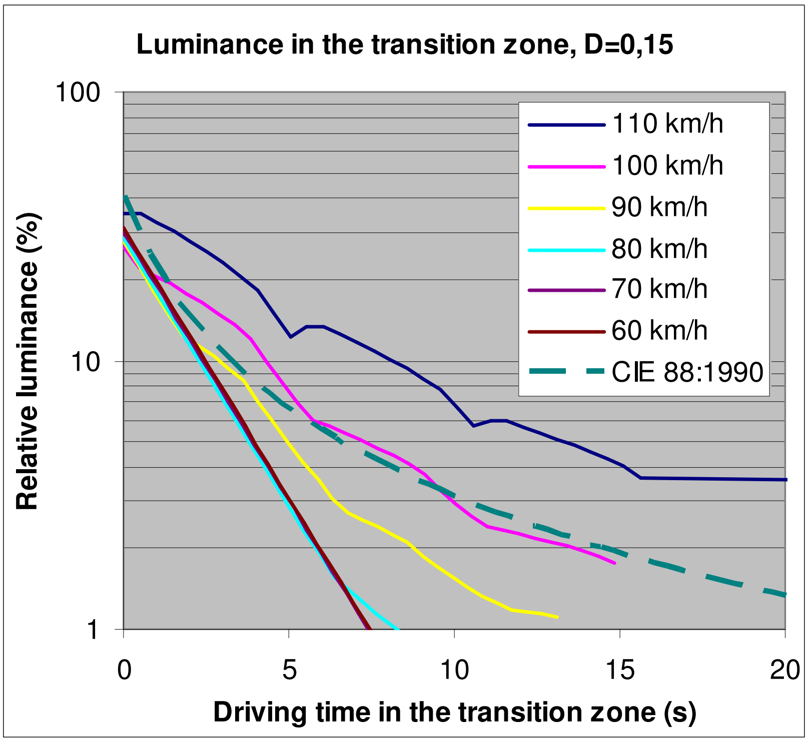


Figure B.13: Luminance profiles in the transition zone for a degree of glare D equal to 0,15.



The profiles start at approximately 30 % followed by decreases with different slopes, most steep for the lowest driving speed and less steep for the highest driving speed. Additionally, the slopes depend on the degree of glare D.

The profile defined in CIE 88:1990 is included for comparison.

It is suggested that use of a single luminance profile for the transition zone, as is CIE 88:1990, may be too simple.

B.8 Visibility levels at other driving speeds than the design driving speed

Figure B.14 shows the visibility levels at other driving speeds than the design driving speed. The figure applies for the inner zone and a requirement of a minimum VL value of 5 at the design speed.

Figure B.14: Actual VL values depending on the actual driving speed.

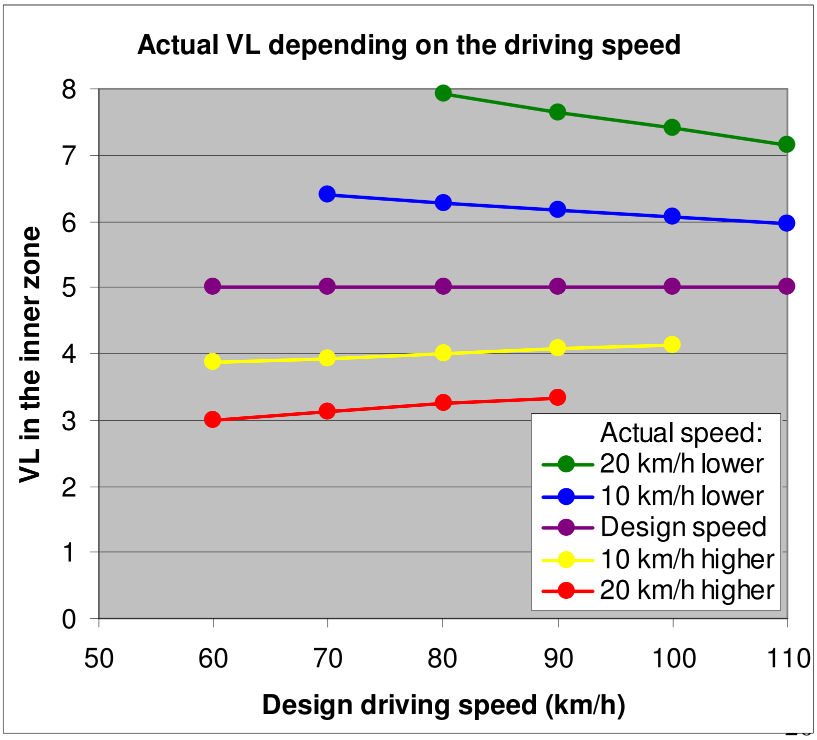


Figure B.14 shows that the VL value does depend on the actual driving speed compared to the design driving speed.

At the design driving speed, the VL value equals the minimum required VL value, else it is higher or lower by approximately 1 for each change of the actual driving speed by 10 km/h. The reason is that the driver observes the object from a distance that is different from the stopping distance at the design driving speed.

This means that a driver can improve visual performance by reducing the driving speed.

This applies not only for the interior zone, but also for the threshold and transition zones. In these zones, the effect is actually larger for the reason that the driver gets to a location with less glare, when he gets closer to the object. Simultaneously, the t_{10} value increases with decreasing speed, so that visual comfort is also improved.

In total, a driver can improve the visual conditions strongly by reducing the driving speed. Some drivers probably do that instinctively.

Example: With a design driving speed of 90 km/h and an actual speed of 70 km/h, the VL value is raised from 5,0 to 8,0 at the tunnel entrance and from 5,0 to 7,7 in the interior zone. The t_{10} value is raised from 5 to 6,2 seconds.

A higher driving speed is, on the other hand, at a cost of reduced visibility conditions.