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MEMO CONCERNS

Disturbing light at road work places - disability glare

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Summary

To carry out road works effectively, road works are more and more frequently carried out during night-time. This implicates rerouting of the traffic to road conditions that are unknown and unusual to the motorist. These conditions represent a challenge to the road user, and it is important to provide conditions which otherwise are good to ensure safe operation of the vehicle. This is done by proper signing and visual guidance. Driving during dark hours may be demanding, and it is important that the visual conditions at these work places acceptable for safe driving. Disability glare caused by light at the construction site and the road traffic itself should be under control. The glare could be caused by permanent installations or lighting on the transport vehicles. The standards for low beams represent a compromise between the needs for good illumination of the road and the importance of avoiding glare to the opposing traffic. But the unusual conditions at the road work places may involve that the presumptions are not met: the illumination of the road may be poor and the glare to other motorist may be bad. Methods for describing discomfort glare and disability glare are described and recommended levels are referred. Full scale tests are done to investigate the glare level caused by lighting equipment used in connection with road workplaces. Glare caused by opposing cars is investigated by computer simulations. In many situations glare levels higher than those recommended for ordinary road lighting will easily appear. Recommendations are given for how lighting equipment should be chosen and installed. Methods showing how finished lighting installations could be checked are given.

CONTENTS

1 Background

To carry out road works effectively, road works are more and more frequently carried out during night-time. This implicates rerouting of the traffic to road conditions that are unknown and unusual to the motorist. These conditions represent a challenge to the road user, and it is important to provide conditions which otherwise are good to ensure safe operation of the vehicle. This is done by proper signing and visual guidance. Driving during dark hours may be demanding, and it is important that the visual conditions at these work places acceptable for safe driving. Disability glare caused by light at the construction site and the road traffic itself should be under control.

The glare could be caused by permanent installations or lighting on the transport vehicles.

The standards for low beams represent a compromise between the needs for good illumination of the road and the importance of avoiding glare to the opposing traffic. But the unusual conditions at the road work places may involve that the presumptions are not met: the illumination of the road may be poor and the glare to other motorist may be bad.

2 Methods to describe glare

It is common to distinguish between two types of glare, discomfort glare and disability glare.
To describe glare by computations and measurements suitable theoretical models and methods for measurement are needed.

2.1 Discomfort glare

Discomfort glare is a psychological feeling of discomfort experienced when light sources with high luminances appear in the field of vision. Some retinal diseases may enhance this feeling. Different theoretical models are used for indoor and outdoor lighting installations, but we will describe only one method used for outdoor installations.

For a certain luminaire designed for outdoor use its cause to discomfort glare can be described by its discomfort glare rating (DGR). DGR when the luminaire is observed from a certain direction is described by:

$DGR = {}^{I}\!\big/\!{}_{\sqrt{A}}$	equation 1

where:

I is the luminous intensity in the particular direction (candela)
A is the luminous area of the luminaire seen in the particular direction (m^2)

The limiting DGR is the maximum DGR found for directions with angles between 85° and 90° with nadir for all directions around the luminaire. The limiting value of DGR is 500 for luminaires used in dark surroundings and 1000 when used in bright surroundings (ref. 3, ref. 6).
It is apparent from the definition that DGR is a figure describing one luminaire in a special situation and not a complete lighting installation.

2.2 Disability glare

The disability glare is physiological and describes a negative influence on the visual conditions. Light from a (glaring) light source is scattered by ocular media and is imposed on the image on the retina. It reduces the contrast of the image and the visual target becomes more difficult to observe. The contrast reduction can be described as if an even veil is drawn in front of the visual scene. The luminance of this veil is called 'the equivalent veiling luminance'.

2.2.1 Equivalent veiling luminance

The equivalent veiling luminance L_v caused by one light source (Figure 1)

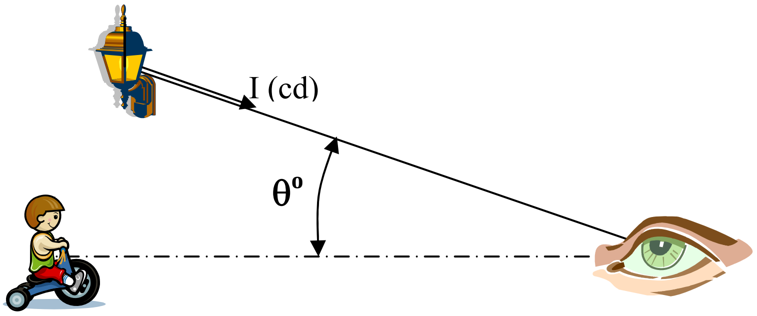


Figure 1. The angle θ in disability glare

is found by the so-called Stiles-Holladays glare formula for point sources:

$L_v = 10 \bullet E_{bl} / \Theta^2$	(cd/m^2)	equation 2

where:

10 is an age depending factor. The value of 10 is valid for an average, young person

θ is the angle between the direction towards the observed target and the direction towards the glare source, measured in degrees (°)

E_{bl} is the illuminance caused by the light source on a plane at an right anggle to the direction of view, just in front of the observers eyes (lux)

The valid interval for equation 2 is $1^o \le \Theta \le 30^o$.

E_{bl} is calculated from:

$E_{bl} = \frac{I}{d^2} \bullet \cos\Theta$	(lux)	equation 3

where:

I is the luminous intensity of the glare source against the eyes of the observer (cd)

The amount of stray light in the eye increases by the age. If this effect should be accounted for,
CIE recommends that the so-called age adjusted Stiles-Holladays glare formula is used (ref. 4):

$L_v = 10 \bullet \frac{E_{bl}}{\Theta^2}\left(1+\left(\frac{A}{70}\right)^4\right)$	(cd/m^2)	equation 4

where:

A is the age of the observer (years)

The equivalent veiling luminances for a person 40 years of age, calculated using equation 4, are approx. 10 % higher than calculations using equation 2, and 100 % higher for a person 70 years of age.

Lighting installations consist of several luminaires. With n light sources, the contribution from each of them must be added to find the total effect. From equation 2 we will then get:

$L_v = 10 \bullet \sum_{i=1}^{n}\left(E_{bli} / \Theta^2{}_i\right)$	(cd/m^2)	equation 5

The age effect is not considered in this formula.

2.2.2 Threshold increment as a measure of disability glare

In road lighting and other types of outdoor lighting it is usual to supplement the description of disability glare by the threshold increment, TI. TI describes how much the contrast between the actual object and its background has to be increased for the object to be as visible with glare as it was without glare. TI is determined from:

$TI = 65 \cdot L_v / L^{0,8}$	(%)	equation 6

where:

L_v is the equivalent veiling luminance (cd/m^2)
L is the adaptation luminance of the observer (cd/m^2)

The formula is valid for the interval $0,05 \text{ cd/m}^2 < L < 5 \text{ cd/m}^2$. This is sufficient for use in roadway lighting.

I Mörkertrafik rapport nr. 1 (ref. 5) it is proposed that the veiling luminance caused by lighting installations should be limited as shown in Table 1. In the table equation 6 is used to transform the limiting veiling luminance to limiting threshold increment, TI.

Table 1. Recommended glare control from Mörkertrafik rapport nr. 1 (ref. 5)

Road lighting type	Average luminance of the road	Maximum glare (equivalent veiling luminance)	Maximum Threshold Increment, TI
Unlit road	-	0,050 cd/m^2	
Road lighting	0,5 cd/m^2	0,068 cd/m^2	7,7
	1,0 cd/m^2	0,140 cd/m^2	9,1
	1,5 cd/m^2	0,200 cd/m^2	9,4
	2,0 cd/m^2	0,280 cd/m^2	10,5

CIE states that threshold increments lower than 2 can be neglected (ref. 1). Further more CIE recommends that for a road lighting installation TI should be lower than 10 % and never higher than 15 % (ref. 3). It can be observed that the recommendations from CIE are more moderate than the recommendations in "Mørketrafikk nr. 1".

2.2.3 Visual search when driving and its influence on adaptation luminance

No recognised methods are known to determine the adaptation luminance when driving using dipped headlights, but it is stated that when driving on lit roads, the adaptation luminance can be taken as the road luminance (ref. 1).

It is acknowledged that those parts of the visual field being closest to the direction of view have a dominating influence on the adaptation luminance, and also that the adaptation luminance is a dynamic figure varying with time.

Investigations have shown how drivers are searching the visual field when they are driving during daytime. Examples of this type of results are shown in Figure 2 and Figure 3.

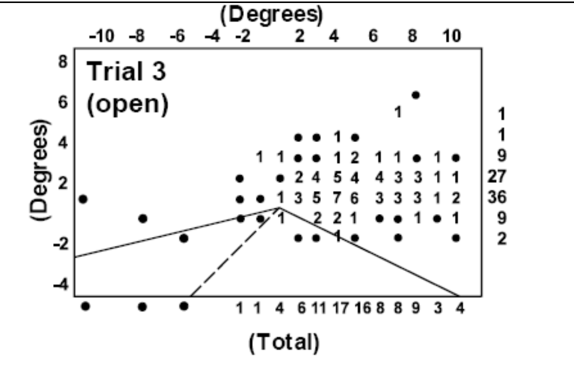


Figure 2. Visual search on open road (ref. 9, from ref. 8)

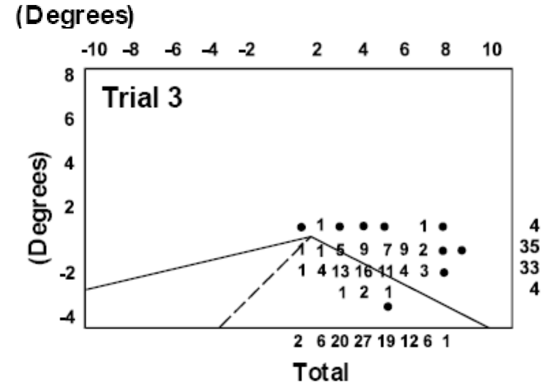


Figure 3. Visual search when following a car (ref. 9, from ref. 8)

The figures show the road with their limitations and the centre line seen in perspective. The spots and the numbers show the percentage of the time when the driver focuses on the spot. These percentages are added horizontally to the right and vertically beneath the figures. It is clear that the driving situation has influence on the seek pattern. It can also be seen that the longest seeking time is spent on the right part of the road and also that many fixations are close to the vanishing point in the horizon and to the right of the roadside.

It does not seem reasonable that the visual field is scanned in the same way when driving in the dark, especially when dipped headlights are used, but it is reason to believe that the scanned part is rather far ahead. The luminances are low in this region due to the limitations in the headlights, and the surroundings are not illuminated at all.

In the tests in Varberg the luminances measured with dipped headlights on dry road surface were approx. 1 - 1,3 cd/m^2 and approx. 0,5 cd/m^2 on wet road, see chapter 3.3.2. In Værløse the illuminance due to the road workplace was approx. 1,8 cd/m^2 on dry road (see Figure 8, chapter 3.1.3). In Linköping the workplace lighting gave a luminance of 1,5 cd/m^2 tog 3,5 cd/m^2 on dry road, see chapter 3.2.4). It thus seems reasonable to suggest that the adaptation luminance of the driver is clearly lower than 1 cd/m^2 when driving with dipped headlights on dry road and clearly lower than 1 cd/m^2 when driving on wet roads. Driving on lit workplaces, the tests indicate that the adaptation luminance will be approx. 1,5 cd/m^2.

2.3 Practical methods for glare control

When photometric data for the glaring are unavailable, D and L_v can be calculated for the actual directions. On the contrary, a lighting installation can not be measured in a single reading or calculated from readings and equation 1, equation 2 or equation 4 directly. Portable instruments suited for the measurement of parameters of the formulas (luminous intensity I (cd), area A (m^2), E_{bl} (lux)) are not available. The occurring illuminances are very low and are impossible to measure with the necessary accuracy with portable instruments. In addition it is a demanding task to measure the glare illuminance from each glare source separately.

A method for field determination of disability glare is described in the following. It is based on equation 2.

2.3.1 How to determine the equivalent veiling luminance from field measurements

This method goes through two steps. At first the illuminance from each of the glare sources is measured. Then the angle between the direction of view and the direction towards the glare source is determined.

2.3.1.1 Illuminance measurements by the use of a luminance meter

It is required in equation 5 that the contribution from each of the glare sources is measured independently. If there are more than one glare source it is practically impossible to do the measurements by the use of a conventional illuminance meter. One can imagine that the photometric cell is provided with a long, narrow tube to limit the part of lighting installation that is contributing to the instrument reading. But this approach is not feasible for lack of a viewfinder and portable illuminance meters are not designed to cope with the very low illuminances normally prevailing.

The description of the instrument required is that of a luminance meter, but it should be calibrated in lux. This can be done as it can be seen from the following photometric relations. Luminance can be written as

$L = I/A$ (cd/m^2), i.e. $I = L \cdot A$ (cd)

and the illuminance as

$E = I/r^2 = L \cdot A/r^2 = k \cdot L$	(lux)	equation 7

where:

$k = A/r^2 = \pi \cdot b^2/r^2 = \pi \cdot (r \cdot \alpha \cdot \pi/180)^2 / r^2 = \alpha^2 \cdot (\pi/180)^2 = 3{,}05 \cdot 10^{-4} \cdot \alpha^2$	equation 8

where:

b is the angle of arc equal to the angle α

α is the angle constituted by measuring field of the luminance meter, in degrees

The supplier always states the angle of the measuring field in degrees. The accuracy of this specification is not important for normal use. But for our special use the size of this angle is critical. Consequently the value of k has to be found by calibration.

For the calibration a small light source having a high luminous intensity is needed. It should be placed in the centre of the measuring field, and the rest of the measuring field should be as dark as possible. The measuring distance should be at least 2metres to 3 metres. The reading L_m for the average luminance in the measuring field is taken, and the illuminance E_{lum} is measured in the plane of the front lens of the luminance meter. We then have:

$k = E_{lum} / L_m$	equation 9

Luminance meters have advanced electronics to transform the low light levels to accurate readings.

2.3.1.2 Determination of the angle to the glare source

The angle to the glare source can be determined by the use of an angle meter, which can be obtained from a tool supplier, but it must be provided with some sort of aiming devices. But perhaps the most practical way is to determine the angles from a photograph. The photograph makes it possible to determine the angle to any point at any time, and it serves as documentation of the situation at the measuring time.

The photograph is taken by a digital or film based camera, but it will simplify the use if it has a lens with fixed focal length (not a zoom lens). It should not be a wide-angle lens. The camera must be calibrated to establish the relations between distances in the picture and the distances in the real world. For the calibration the camera must be mounted on a tripod and a picture is taken at right angle to a large wall, as free from disturbing objects as possible. The distance s between the camera and the wall must be measured. Two points are marked on the wall, the central point in the picture and an arbitrary point within the frame of the picture. The distance d between the two points must be measured.

When the picture is available, the distance b_{cal} between the two points in the picture is measured and the factor m calculated:

$m = b_{cal} / d$	equation 10

When the picture of the glaring lighting installation is ready, the distance b_{mea} between the point defining the direction of view and the glare source is measured. The angle Θ between the two directions can then be found from:

$\Theta = \tan^{-1} (b_{mea} / (s \cdot m))$	(grader)	equation 11

The aiming direction of the camera when pictures for the angle measurements are taken should be that of the actual viewing direction. All pictures should be taken with a lens of the same focal length, pictures for calibration and measurement should have the same magnification and d, b_{cal}, s og b_{mea} should all be measured by the same units.

2.3.2 Calculation of the equivalent veiling luminance

When the illuminance E_{lum} (just in front of the luminance meter, at right angle to the direction from the luminance meter to the glare source) has been determined using the reading from the luminance meter and equation 8 or by calibration and equation 9, and the angle Θ between the direction of view and the direction to the glare source is determined photographically using equation 11, the equivalent veiling luminance is determined from:

$L_v = 10 \cdot E_{lum} \cdot \cos \Theta / \Theta^2$	(cd/m^2)	equation 12

3 Report from the full scale tests

Different test situations where both experts and lay people did driving tests were built in full scale at Værløse close to Copenhagen, Linköping and Varberg in Sweden. Topics related to the lighting and glare conditions are dealt with in the following.

3.1 Værløse in March 2006

3.1.1 Introduction

Tests and measurements were performed the in March 28 - 29 in 2006 at Værløse Flyvestation, Copenhagen, Denmark. The test site simulating a work place on the right-hand side of a road was designed according to Danish road regulations. A tower approximately 9 m high was raised near the road kerb to provide the work place lighting. The first night three 1000 W symmetrical tungsten halogen floodlights made by Cariboni were mounted in the tower. The second night they were substituted by two Idman Philips Ville 510 HVM luminaires modified to use SON-T 150 W lamps.

3.1.2 Test equipment

The first and second night a digital camera Canon Digital EOS 350D with a Sigma 18 - 50 mm f/2,8 EX DC zoom lens was used to take photographs of the test scene. The luminances were measured in selected areas with a Lichtmesstechnik LMT L1009 luminance meter. The second night a LMK96 digital measuring system from the TechnoTeam company was used. In principle it works as an imaging luminance meter where the luminance in each pixel can be read.

3.1.3 Results

The measuring situations on the two days are shown in Figure 4 and Figure 5. Notice the differences in glare and the illuminated areas. The pictures also show warning lights on the top of the guiding signs.

Figure 4. Measuring situation with three 1000 W symmetrical tungsten halogen floodlights made by Cariboni were mounted in the tower

Figure 5. Measuring situation with two Idman Philips Ville 510 HVM luminaires modified to use SON-T 150 W lamps, wet or humid concrete

The measuring fields are shown in Figure 6, which is a schematic presentation of Figure 4 and Figure 5.

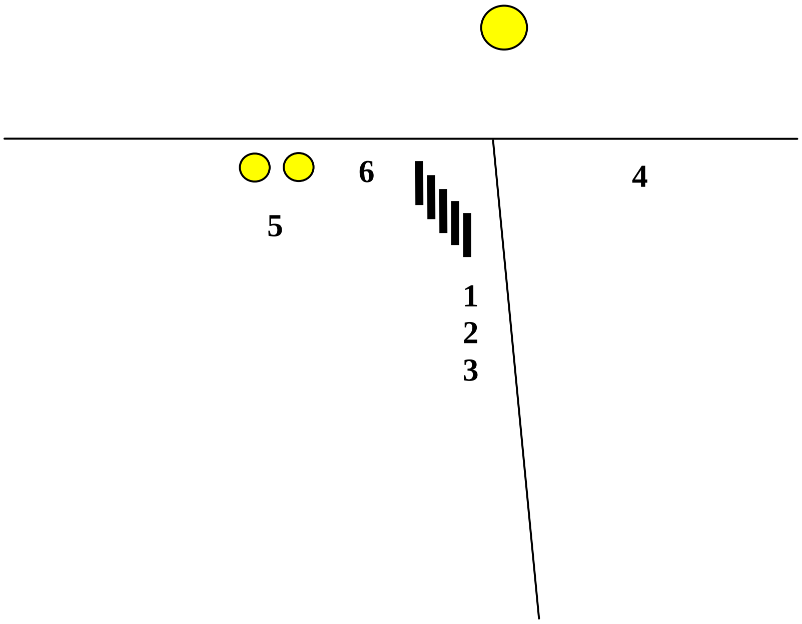


Figure 6. Sketch of set-up. Two lines resemble the horizon and the border between grass and concrete

In Figure 6 the two yellow rings to the left illustrate a car with headlights switched on. The upper yellow ring illustrates the workplace lighting (tower). Measurement spot 1-3 are on the asphalt surface in front of the flashing lights. Measurement spot 4 is on a brighter stripe of light from the tower, on the grass. Measurement spot 5 is the image of the car headlights in the asphalt. Measurement spot 6 is a brighter stripe of light on the asphalt (the same stripe as number 4).

Luminance measurements were mostly taken on the first night (dry concrete). Similar values were obtained on the second night. There were some changes from the first night. The road surface was wet or moist and the headlights and the floodlights were changed, giving different values for these objects. The values for the two nights are given in Table 2 and Table 3.

Table 2. Luminance measurements with three 1000 W symmetrical tungsten halogen floodlights made by Cariboni were mounted in the tower.

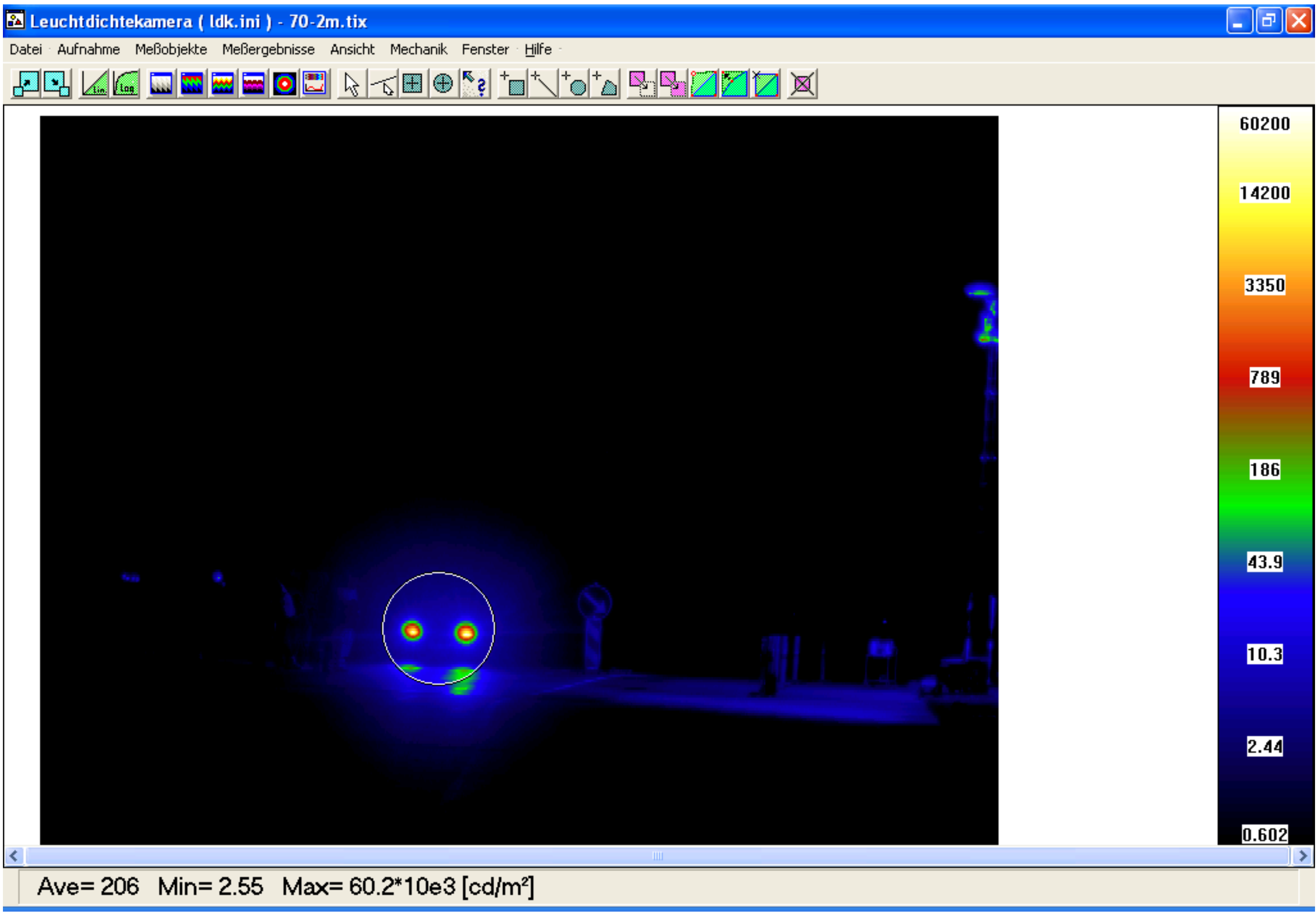
Measure-ment	Measuring distance 70m		Measuring distance 120m		Measuring distance 170m
Point no.	Average luminance (cd/m^2)	Measuring field (circular)	Average luminance (cd/m^2)	Measuring field (circular)	Average luminance (cd/m^2)
1	5.	20’			
2	4.4	20’			
3	3.9	20’			
4	3.9	20’			
5	15-30				
6			3.36	20’	
Tower 1st night	2140	1°	170	1°	62
Right headlight	200	1°			
Left headlight	300	1°			
Headlights (both)	2960	1°	135	1°	100

Table 3. Luminance measurements with two Idman Philips Ville 510 HVM luminaires modified to use SON-T 150 W lamps mounted in the tower

Measure-ment	Measuring distance 70m		Measuring distance 120m		Measuring distance 170m
Point no.	Average luminance (cd/m^2)	Measuring field (circular)	Average luminance (cd/m^2)	Measuring field (circular)	Average luminance (cd/m^2)
Tower	1.4	3°	4	1°	
Headlights (both)	48	3°	245	1°	

The method described in chapter 2.3 can also be used in combination with the LMK96 system. The system has a large dynamic range by taking a series of pictures with increasing exposure time and combining them. Resulting pictures in false colour are shown in Figure 7 to Figure 10. The scaling used for the colours is shown at the right-hand side of the picture. Average (Ave), minimum (Min) and maximum (Max) luminances in the measuring field are shown at the bottom of the picture. Figure 7 and Figure 8 both show the same left-hand side of the test scene, but luminance values are indicated (at the bottom) for different measuring fields. Figure 9 and Figure 10 show the same procedure for the right-hand side of the test scene. Figure 8 and Figure 9 show the same part of the test scene, but both are included to show that though the pictures appear different because of the different scaling (the scaling takes into consideration the highest luminance in the picture) the adaptation luminances are identical. Figure 9 also gives a better indication of the details in the scene.

A field of 2° is defined as the measuring field for the car to the left in Figure 7 and the luminaires in the top of the tower in Figure 10. A rectangular field around the driver's direction of view was defined to represent the adaptation field. It has the same size in both Figure 8 and Figure 9.



```
Ave= 206   Min= 2.55   Max= 60.2*10e3 [cd/m²]
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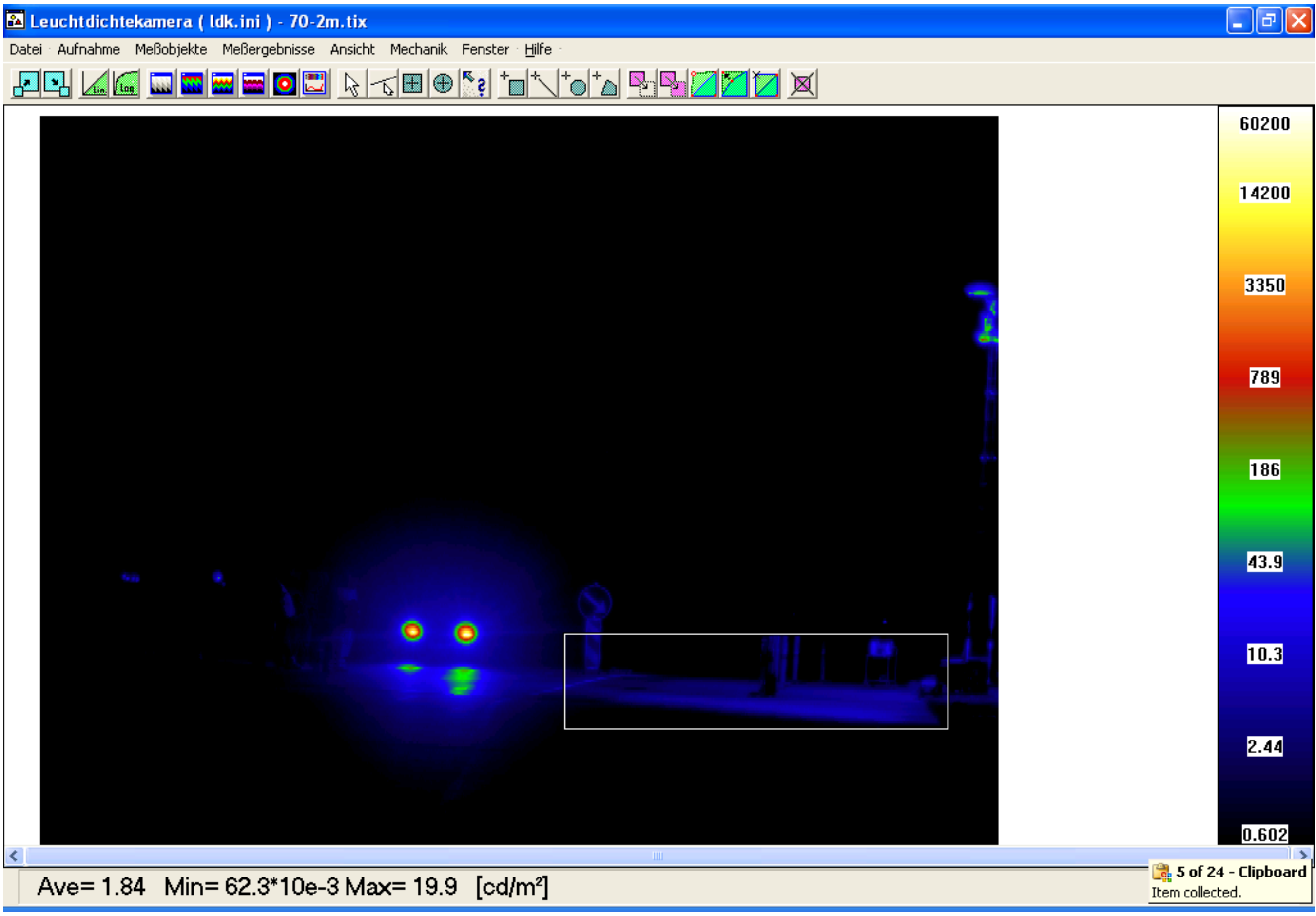
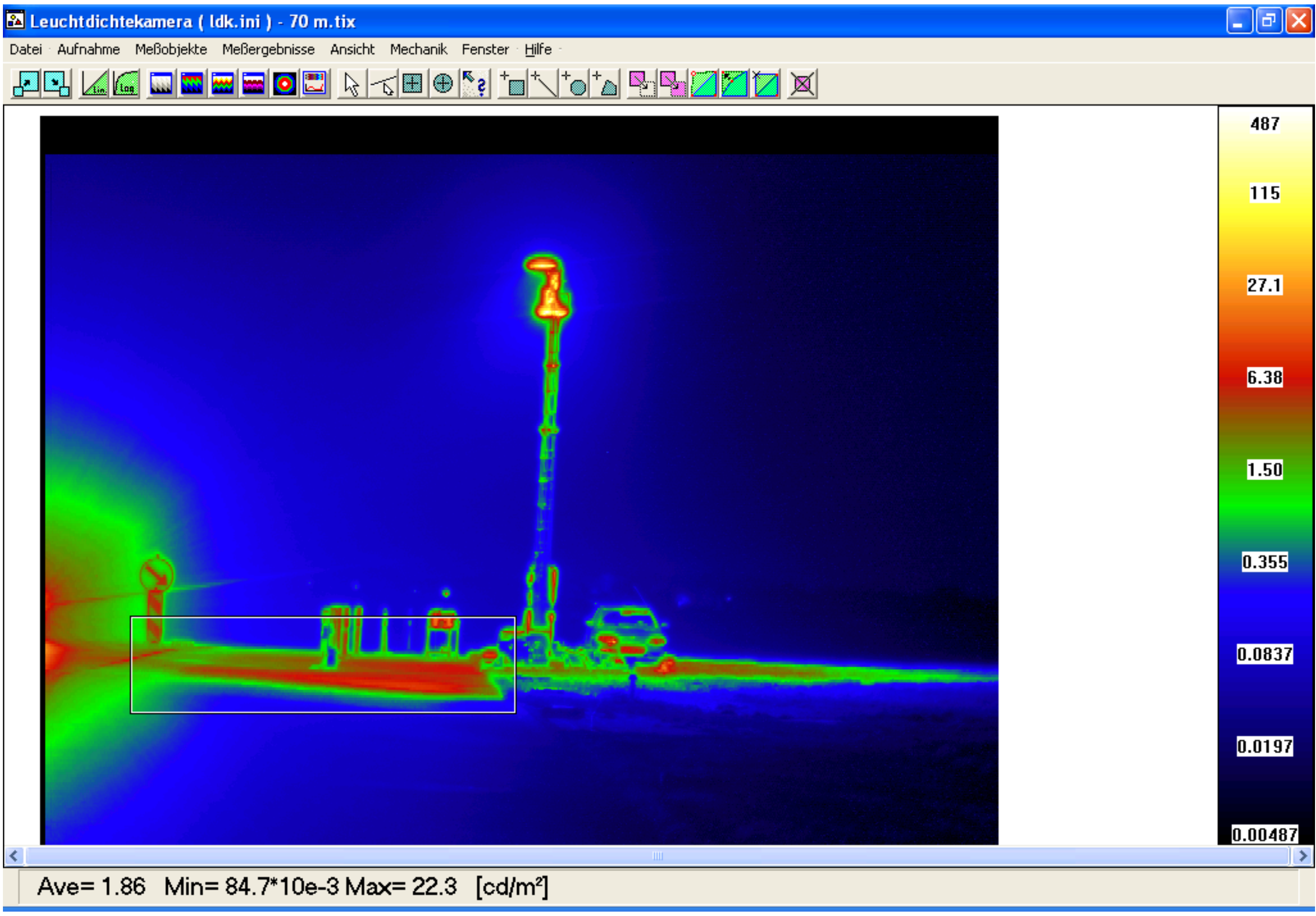
Figure 7. False colour presentation of left-hand part of test site on the second night (2006-03-29), with 2° measuring field and its luminance values



Ave= 1.84 Min= 62.3*10e-3 Max= 19.9 [cd/m²]

Figure 8. False colour presentation of right-hand part of test site two Idman Philips Ville 510 HVM luminaires modified to use SON-T 150 W lamps in the tower, with rectangular measuring field (taken as adaptation field) and its luminance values



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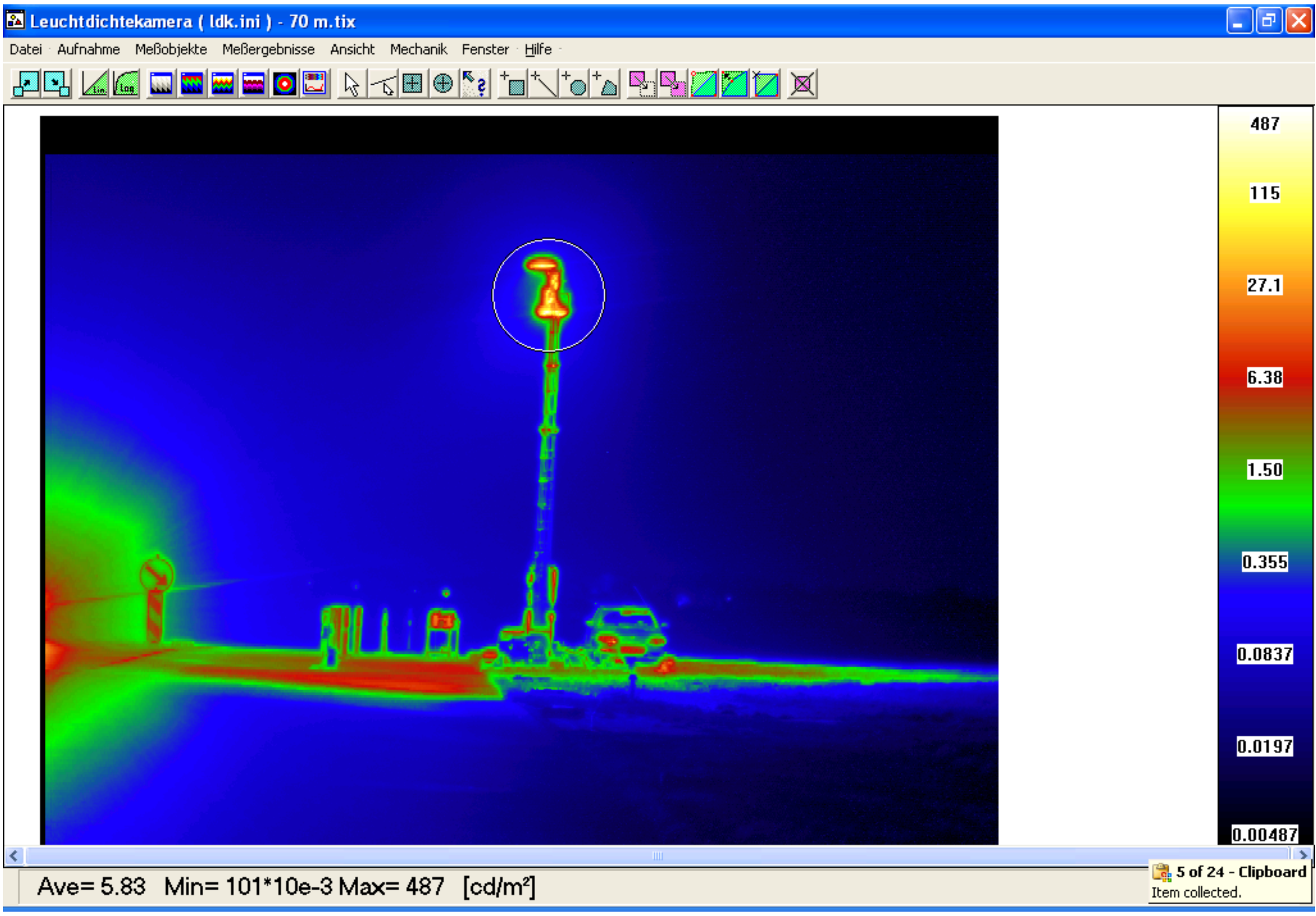
Ave= 1.86   Min= 84.7*10e-3 Max= 22.3   [cd/m²]
```

Figure 9. False colour presentation of left-hand part of test site two Idman Philips Ville 510 HVM luminaires modified to use SON-T 150 W lamps mounted in the tower, with rectangular measuring field (taken as adaptation field) and its luminance values



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Ave= 5.83   Min= 101*10e-3 Max= 487   [cd/m²]
```

Figure 10. False colour presentation of the test site two Idman Philips Ville 510 HVM luminaires modified to use SON-T 150 W lamps mounted in the tower, with 2° measuring field and its luminance values

Using data from Table 2 (tungsten halogen floodlights) and the method described in chapter 2.3 and 2.2.2 the threshold increment is in this case TI = 6,7. This is calculated for an approaching driver with an adaptation luminance of 1,85 cd/m^2 (average luminance of Ave = 1,84 cd/m^2 in Figure 8 and Ave = 1,86 cd/m^2 in Figure 9) at a distance of 70 m from the work place with a veiling luminance of 0,068 cd/m^2 caused by the opposing car and 0,101 cd/m^2 caused by the luminaires in the tower.

Using the data in Table 3 (SON-T 150 W lamps), the resulting threshold increment, taking into consideration the opposing car and the luminaires in the tower is in this case TI = 2,7. The contribution from the car to the veiling luminance was 0,068 cd/m^2 and from the tower 0,00035 cd/m^2.

3.2 Linköping in October 2006

3.2.1 Introduction

Tests and measurements were performed the in the evening and the night between October 12/13 on highway 636, close to Linköping, Sweden. The test site simulating a work place on the right-hand side of a road was designed according to Swedish road regulations. A sketch of the test site is shown in Figure 11. The traffic signs are not shown however.

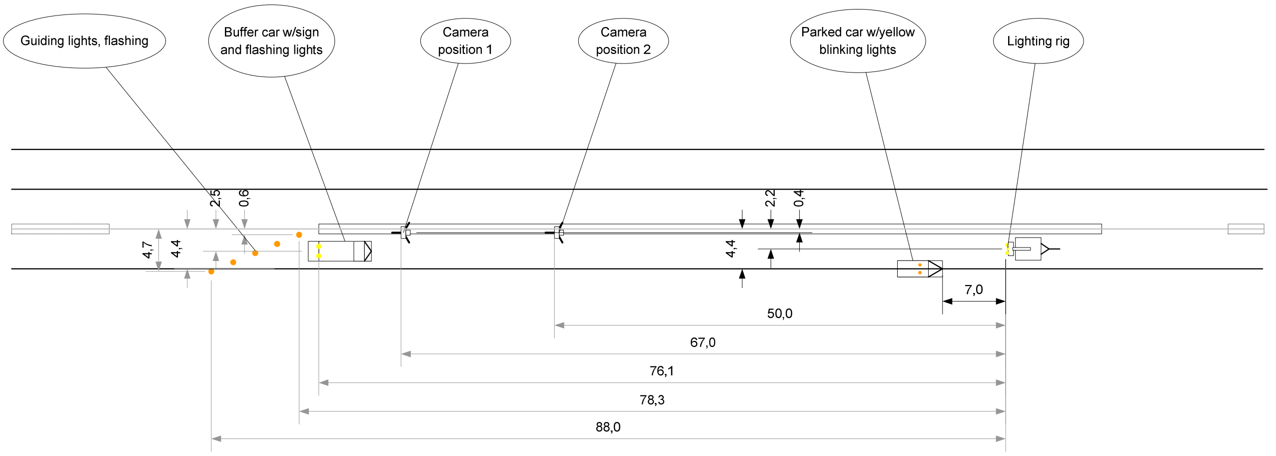


Figure 11. Sketch of the test site (to scale)

3.2.2 Lighting for the tests

It is a popular understanding that by using tilted luminaires it is possible to illuminate larger areas with fewer luminaires. In the tests this method was tested with a luminaire type Philips MVF 300 fitted with a 250 W metal halide lamp tilted 45°. An alternative solution with two Idman Philips Ville 510 luminaires modified to use SON-T 150 W lamps was also tested. These luminaires were mounted with the front glass horizontal. Both luminaire types had a flat front glass, see Figure 12. The luminaires were mounted in a mobile lighting mast approximately 9 m high was raised near the kerb side of the road.

Figure 12. Two types of luminaires to demonstrate the traditional lighting method (dark luminaire) and an alternative method (light luminaire)

Five running warning lights were used to inform the drivers about the redirection of the traffic around the work place. Different operating modes of these warning lights were part of the experiment. A mobile warning trailer with two flashing lights at the top was placed just behind the running lights. A Volvo estate car was parked on the roadside some 70 metres further behind the trailer. The normal parking lights of the Volvo were lit together with a flashing warning light on its roof.

Test drivers reported and commented on their return from the drive. The purpose of the test was to get data showing how drivers reacted to situations where they were forced to manoeuvre around a road work place when they at the same time were exposed to realistic level of glare from the work place. Among these glare sources, the luminaires in the mast are the main contributors, and they are the main objects of the glare calculations.

3.2.3 Measuring equipment and method

A TechnoTeam LMK Mobile advanced instrument was used to measure the luminances in the visual field of drivers approaching the work place. That instrument consists of a standard digital camera Canon Digital EOS 350D with a Sigma 18 - 50 mm f/2,8 EX DC zoom lens in combination with LMK 2000 software. In order to work as a luminance metering system, the software relies on calibration data for the combined camera body and lens system. The system measures the luminance in every one of the 3456 x 2304 pixels (8 Megapixels). This system has a repeatability of 1,3 % and a measuring uncertainty of 5,8 %.

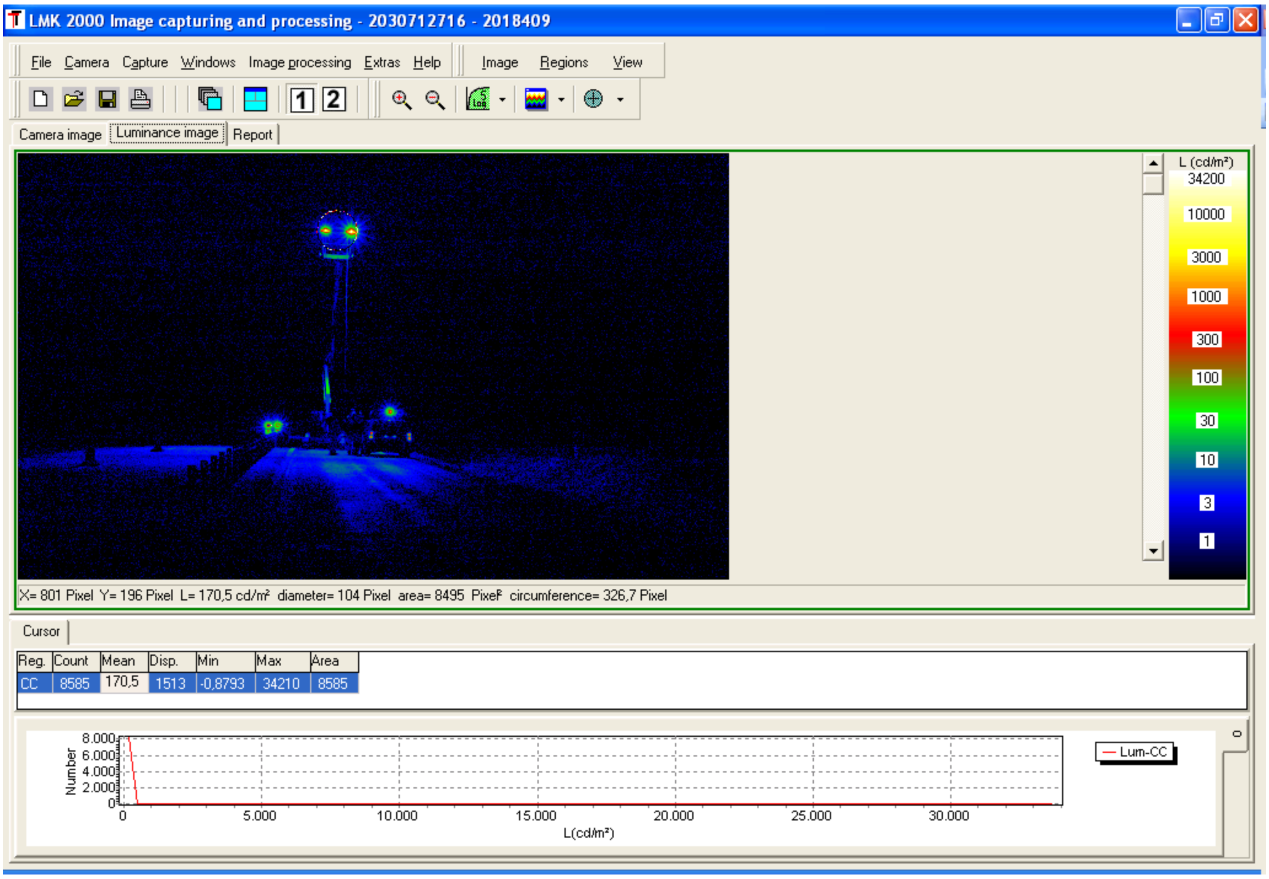
In some of the test situations, the floodlights were aimed towards the test drivers, resulting in that the discharge tube of the lamp was visible. This part of the lamp has an extremely high luminance. To capture this high luminance, overexposure of the discharge tube had to be avoided. By defocusing the camera, the average luminance of a area larger than the luminaires was measured. From this the luminous intensity of the glaring luminaire could be calculated.

For the safety of the test personnel, it was not possible to take measurements from positions on the road. Data necessary for calculating glare on the road are based on luminances measured at the protected positions very close to the road. Closing the road to make the measurements from positions on the road was considered not necessary. It is estimated that the calculated glare parameters will be very good representations of the glare experienced by the drivers on the road.

3.2.4 Glare calculations

As mentioned in chapter 2.2.2, TI for road lighting systems should in general be lower than 10 % and never higher than 15 %. The luminance of the work place was measured to be approx. 3,5 cd/m^2 for the situation with two floodlights and 1,5 cd/m^2 for one floodlight. The luminances of the other parts of the road were low as they were unlit, but the dipped headlights of the vehicles provided some light. The sky was dark, and the luminance close to the horizon was measured to approx. 0,02 cd/m^2. On this background, it seemed reasonable to do the calculations for an adaptation luminance of 0,5 cd/m^2. The direction of view has been assumed to be parallel to the longitudinal direction of the road. The methods used are described in chapter 2.2 and chapter 2.3.

Figure 13 shows an example of how the data from the LMK Mobile Advanced are analysed and presented by the LMK2000 software. The luminances are presented in the form of a false colour picture, and the colour coding is shown to the right. The highest luminance in the picture is 34200 cd/m^2. The circular measuring field laid over the floodlights constitutes an angle of 1,5 degrees. In the results field it can be read that its mean luminance is 170,5 cd/m^2.



```
X= 801 Pixel  Y= 196 Pixel  L= 170,5 cd/m²  diameter= 104 Pixel  area= 8495  Pixel²  circumference= 326,7 Pixel
```

Reg.	Count	Mean	Disp.	Min	Max	Area
CC	8585	170,5	1513	-0,8793	34210	8585

Figure 13. Example of output from the LMK2000 software

With these assumptions, the TI is calculated to TI = 14 % for the 1x 250 W metal halide luminaire at a distance of 67 m and TI = 2 for the two luminaires with 1x150 W high-pressure sodium lamps.

Glare was also calculated based on photometric data for the luminaires. According to the photometric data, only the 1x 250 W metal halide luminaire will cause glare. The results for this luminaire for different distances between driver and mast are shown in Table 4.

Table 4. Calculated levels of threshold increment for 1x 250 W metal halide lamp

Distance (m)	10	90	130	210	410
Threshold Increment TI (%)	119	15	14	13	12

3.2.5 Discussion

Having the same set of assumptions, the measured and calculated results are in good agreement. They show that the drivers in some of the test situations were exposed to glare levels considered unacceptable for road lighting. This will be more so as there are other glare sources in the visual field that not are taken into consideration for methodical reasons. These are the running warning lights, the flashing lights of the warning trailer, the lights of the parked Volvo and the headlights of opposing cars.

None of the test drivers reported that the glare level was high. But this may not be obvious to the drivers, as they presumably are focused on the task of finding their way around the work place. This is an easier task than seeing objects that might be located on the road. It is considered that it is not ethically acceptable to test this hypothesis by placing small objects on the road surface.

3.3 Varberg in 2007

3.3.1 Lighting conditions

The light measurements were done from the passenger seat in a brand new Volvo S40 passenger car while it was driving. The fact that the car was brand new should imply that the optical system of the headlamps as well as the bulbs and front lens were of premium quality and condition. The speed was approx. 90 km/h in the first part of the approach to the test site. It was reduced according to the signing to approx. 40 km/h when driving through the site. An imaging luminance meter of the type LMK Mobile 2000 from the company TechnoTeam was used for the measurements. Due to the measuring situation the full dynamic range of the system was not available. The darkest parts are black due to under exposure, and the brightest parts are white due to over exposure in the colour coded iso luminance pictures.

One series of measurements from a driving through the test site is shown in Picture 1 to Picture 6 in Figure 14. Please observe that the scale for the coding is different for the different pictures. Some data for the pictures are shown in

Table 5. The road surface is dry in Picture 1 and Picture 2, and the dipped headlights provide an illuminated area with a luminance of approx. 0,5 – 2 cd/m^2. The borderline has a luminance of approx. 2 – 6 cd/m^2. In the pictures no. 3 to no. 6 the road surface is wet and the luminances are generally lower.

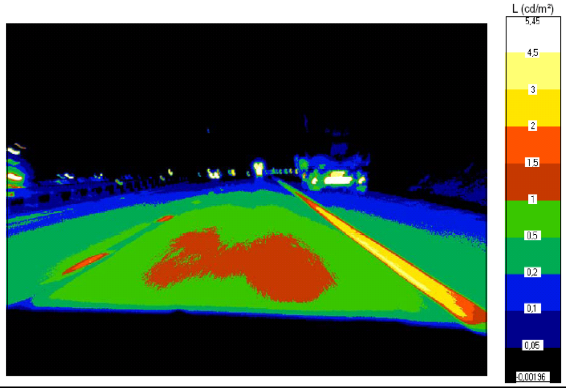
Table 5. Data for the pictures in Figure 14.

Estimated average luminance provided by the dipped headlights (cd/m^2)	Estimated average luminance for right borderline (cd/m^2)	Highest luminance in picture (without over exposure) (cd/m^2)
1,0	2,5	5,45
1,3	4,0	10,2
x	x	2,03
x	x	22,4
x	x	3,85
x	x	2,86

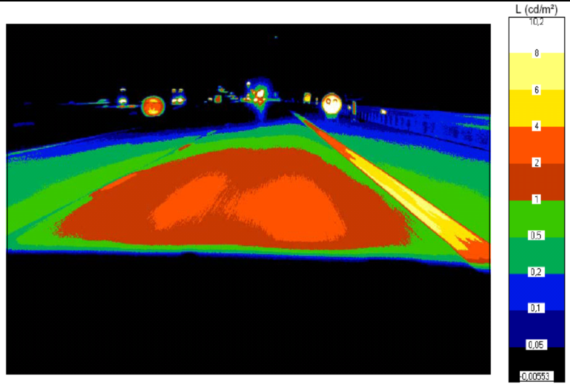
3.3.2 Adaptation luminance for the motorist

Later calculations (in chapter 4) rely on knowledge to the adaptation luminance of the motorist.

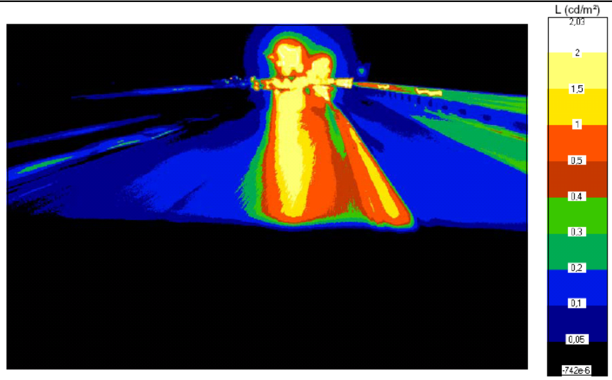
Measurements reported in Picture 1 to Picture 6 in Figure 14 are taken as a basis for an evaluation of this luminance. Provided dry road surface and good conditions the luminances are approx. 1 - 1,3 cd/m^2. When the surface is dry, large parts of the surface had luminances lower than 0,3 cd/m^2. Average luminance of the right borderline is approx. 3 cd/m^2 or 2,5 - 3 times higher.



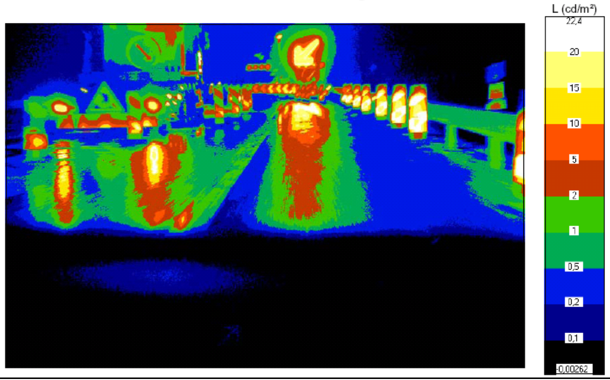
Picture 1.



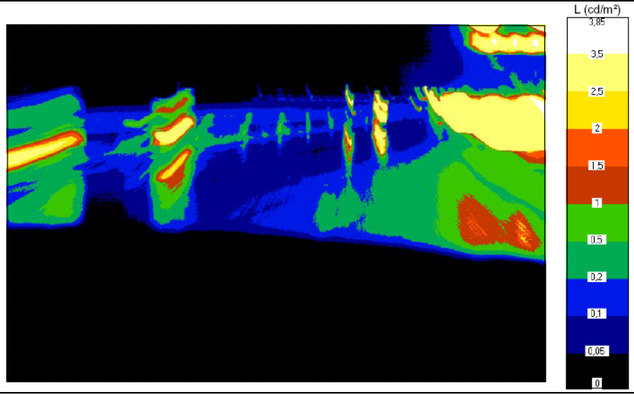
Picture 2.



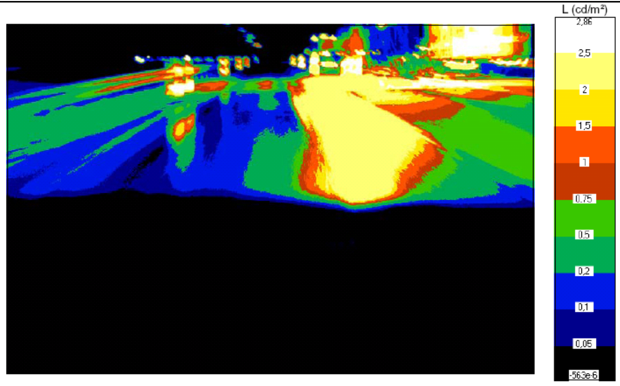
Picture 3.



Picture 4.



Picture 5.



Picture 6.

Figure 14. Iso luminance pictures from the chicane, with two flashing arrows (Varberg)

4 Glare caused by cars in meeting situations

Drivers of passenger cars are believed to be that group of motorists who are most severely affected by the light from opposing traffic. The glare level was analysed by the use of computer program ERGO 2001 from the company Avery-Denison (ref. 7). This program is specially developed for the use in situations with retro reflective signs, but intermediate results offers the possibility to use the program for glare calculations as well.

A database with photometric data for different types of headlights is available, as well as a set of geometric dimensions for some typical vehicles, among these a so-called CEN car. This is so defined that the distance from the road surface to the centre of the headlight is 65 cm, and the height up to the driver's eyes is 120 cm. The CEN car and European dipped headlights as they are defined in a preliminary report from CIE TC 4-20 from 1993 are used in the simulations.

The simulations show the glare level which vehicle X (in the chicane) causes to opposing traffic represented by vehicle Y. A four lane motorway where the two driving directions are separated by a centre strip is used as an example. The driving directions of vehicle X are indicated by red arrows, while green arrows are used for vehicle Y. The situation is shown in Figure 15.

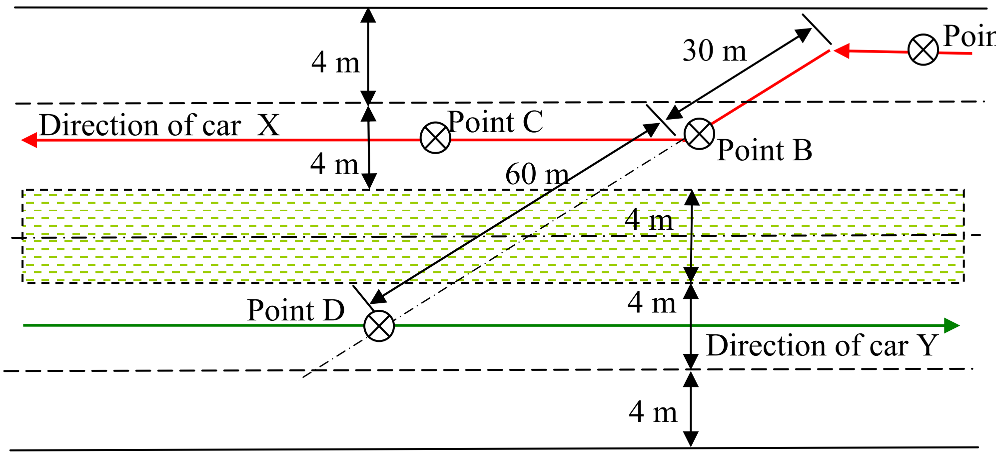


Figure 15. Distances in the chicane used for the calculations of disability glare

The two headlights of the opposing car are calculated separately. Three situations are calculated. In the first situation the glare-causing car is in it outermost lane defined by point A. The threshold increment depends on the adaptation luminance for the situation in question. To fit with the measurements and evaluation of adaptation luminances done as referenced earlier in the report (see chapter 3), the threshold increments are calculated for adaptation luminances in the range from 0,2 cd/m^2 til 1,2 cd/m^2. The results with car X in position A are shown in Figure 16.

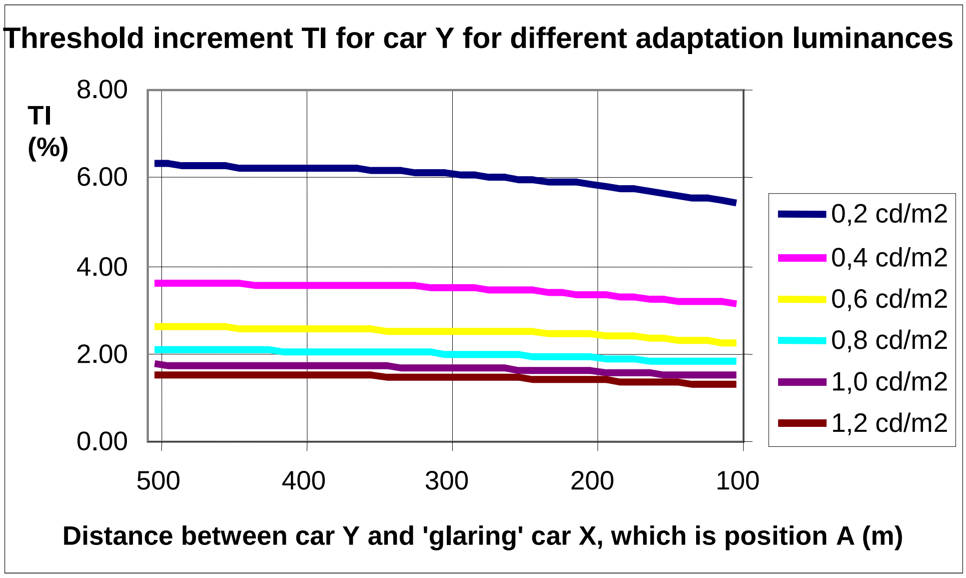


Figure 16. Threshold increment when the glare causing car X is in its right driving lane.

In the second situation, the glare-causing car is at point B. Car Y is driving towards the point D where the directional axes for the cars are intersecting. This area is heavily lit by car X. By negative distances the point D has been passed. The results from this calculation are shown in Figure 17.

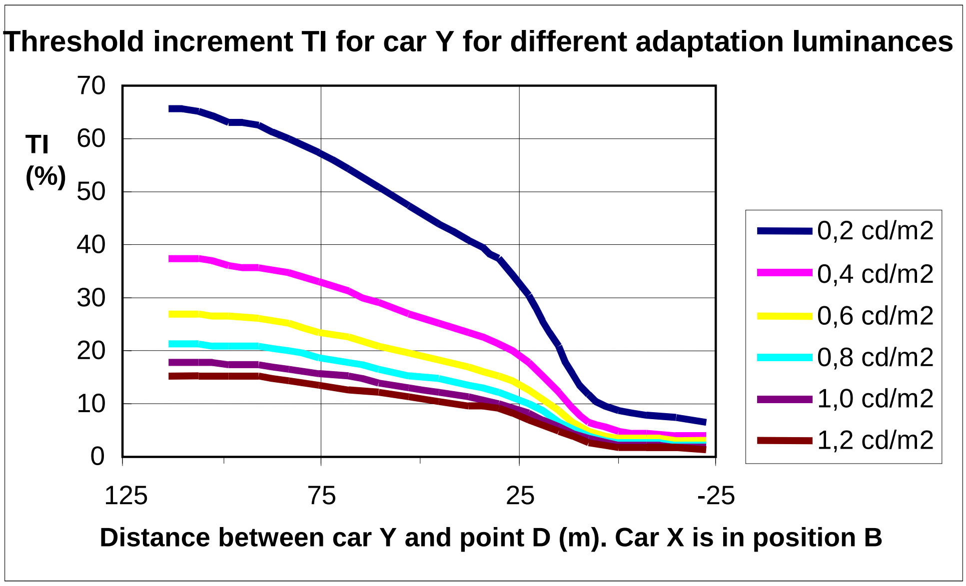


Figure 17. Threshold increment when the glare causing car X has reached the end of the chicane

In the third situation the car X is situated in its left driving lane. The results from this simulation are shown in Figure 18.

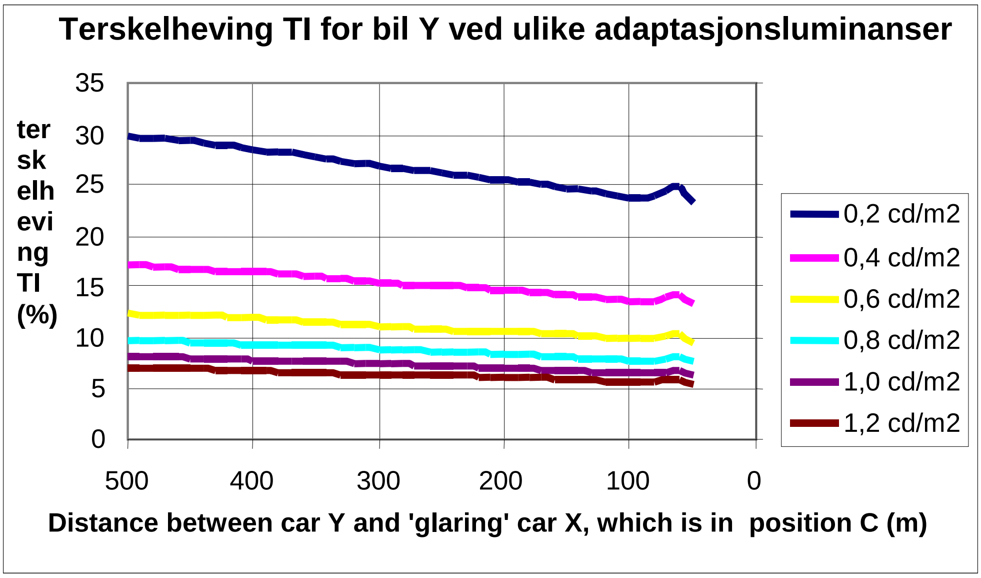


Figure 18. Threshold increment when the glare causing car is in its left driving lane.

Please observe that different scales are used on the ordinate axis. Other geometrical designs of the transition related to the road works could have been analysed in the same way as shown above, but omitted, as they probably would not result in fundamentally new knowledge. Two of the analysed situations are close to being normal meeting situations on a two-lane road, but the distance between the driving directions is larger in the simulations than for a two-lane road. But both simulations show that there is a considerable glare, and that there is a considerable increase in glare when the distance between the driving directions is reduced. But as it is evident from Figure 17 that the situation is most difficult when the cars are on intersecting courses. For this situation steps should be taken to reduce the glare.

When evaluating the results, it should be noticed that the resulting glare levels are the lowest possible. The data used for the simulations are measured for new and clean headlights giving a minimum of stray light. On the road in practical traffic cars with degenerated and dirty reflectors and lamps, misaimed headlights and dirty and wet windscreen can be found.

What has been said so far is related to situations when only two cars are involved. In real traffic, a row of meeting cars may be encountered, and disturbing cars may also be behind the car in question. Glare in practical traffic is anticipated to be far more severe than what the results from these calculations show.

4.1 Screens between the driving directions

One effort to reduce glare between cars is to establish screens between the driving directions. For the screen to be effective, the screen should be opaque in a field preventing direct view of the headlights of the opposing car.

For passenger cars the screen should be opaque in heights from 65 cm to 120 cm, see Figure 19. To provide a good function even for somewhat bigger car, the screen should be opaque in heights from 65 cm to 120 cm. Such screens could be built in such a way that it integrates the function of safety barriers.

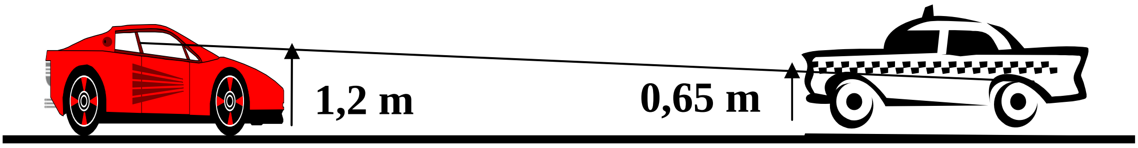


Figure 19. Necessary screen heights depending on where the screen is mounted. Normal passenger car.

For larger vehicles the necessary screens must be even higher, but the situation for the drivers of these types of vehicles is not as critical as they are sitting higher so that the angle between the direction of view and the direction to the glaring headlights becomes higher. Glare is considerably reduced and the screen may be omitted.

An example of such a screen is shown in Figure 20. Its dimensions are not optimal, but even so the use of such screens would be useful.

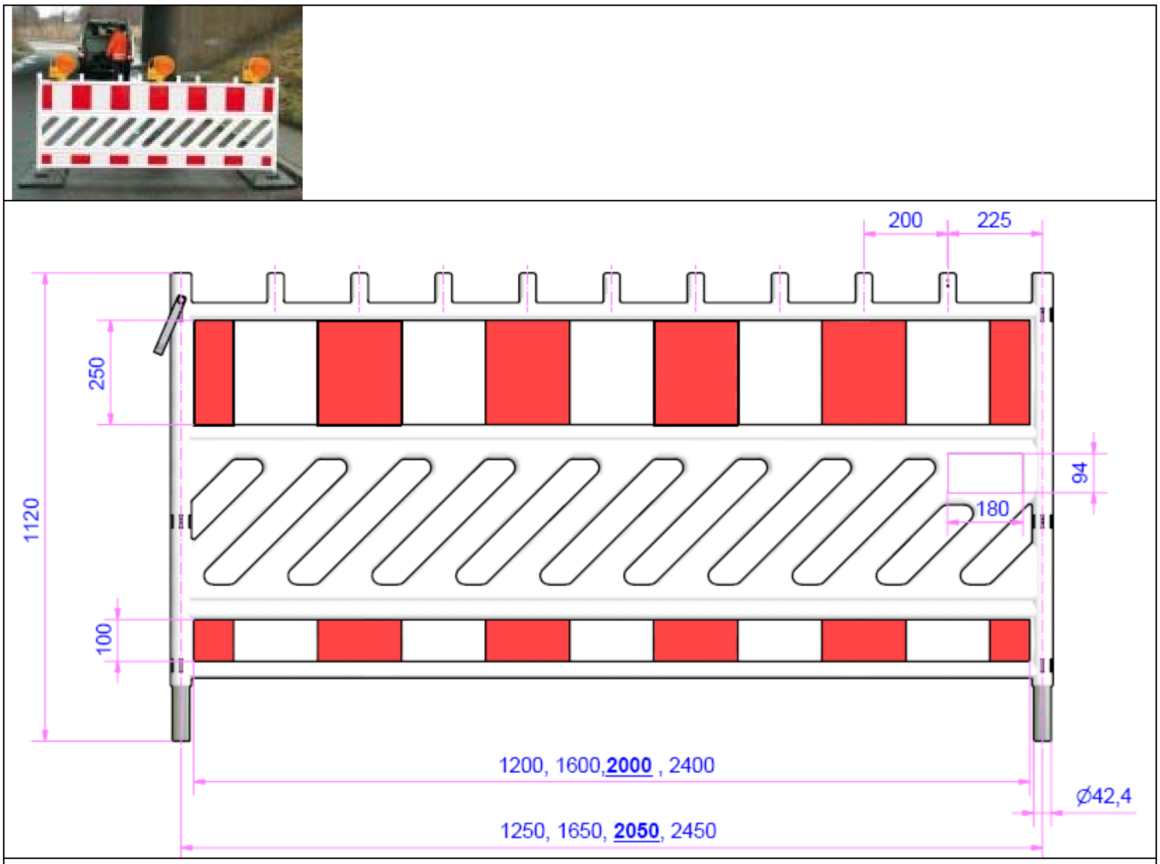


Figure 20. Safety barrier and light screen (not optimal) (Adolf Nissen Elektrobau GmbH + Co. KG, Tönning, Tyskland)

5 Proposed recommendations for glare control

5.1 Illumination of road work places

Road work places should be illuminated. This will counteract the glare effects by increasing the adaptation luminance level as well as providing the drivers with a better understanding of the driving tasks. Temporary lighting installations should be built where the conditions permit it, and permanent installations should be built as early as possible. The luminance level should be at least 0,7 cd/m^2 and the threshold increment equal to 15 % or lower.

5.2 Requirements to lighting equipment

The requirements are connected to the absolute luminous intensities. In this way it is possible to control ready built installations as well as to choose suited equipment at the design stage. The requirements are so adjusted that for luminaires with a mounting height of 7 metres and an adaptation luminance of 0,5 cd/m^2, the threshold increment TI will be less than 15 % for class BB 1, less than 20 % for class BB 2 and less than

30 % for class BB3. For its normal position and adjustment the luminaire should meet the requirements of class BB 2 in Table 6.

Table 6. Classes BB of luminous intensity for luminaires, for recommended glare control

Class	Maximum permitted luminous intensity (cd)			Other requirements
	$\gamma = 70^o$ ^{1})	$\gamma = 80^o$ ^{1})	$\gamma = 90^o$ ^{1})	
BB1	2500	2000	100	Luminous intensities over 90^o should be less than 20 cd
BB2	3300	2700	200	Luminous intensities over 95^o should be less than 20 cd
BB3	5000	4500	300	Luminous intensities over 95^o should be less than 30 cd
1) Valid for angles γ between the nadir and the direction of view when the luminaire is in its normal position and is viewed from the motorists position				

Glare is well controlled is the luminous parts of the luminaire are covered by a flat glass and not tilted more than 5 degrees towards the traffic. The mounting height should not be less than 6 metres. The requirements in Table 6 should be used in combination with photometric data that are measured in a laboratory. It is possible to make field measurements where data is lacking. A possible method is described in Appendix.

5.3 Screens between the driving directions

In the chicane the driving lanes should be separated by light screens. The screens should be opaque in areas between 60 cm and 120 cm above the road surface. Preferably they should be opaque up to 140 cm.

6 References

ref. 1. Commission Internationale de l’Eclairage: ”Glare and Uniformity in Road Lighting Installations”. Publication CIE No 31. 1976

ref. 2. Commission Internationale de l’Eclairage: ”CIE Collection on Glare”. CIE 146:2002. CIE 147:2002

ref. 3. Commission Internationale de l’Eclairage: ”Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic”. CIE no 115-1995.

ref. 4. Commission Internationale de l’Eclairage: CIE COLLECTION on GLARE. 2002. CIE 146:2002. CIE equations for disability glare.

ref. 5. Mörkertrafik rapport nr. 1 , 'Bländing från belysningsanläggningar vid sidan av vägan' (1977)

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http://www.vejregler.dk/pls/vrdad/vr_layout.vis?p_gren_id=3000

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ref. 8. Urban Guide Signs. Guidelines. Literature Review. State of Israel. Ministry of Transport. Department of Land Transport. Jerusalem, October 1999.

ref. 9. Mourant, R.R., Rockwell, T.H.: Mapping Eye-Movement Patterns to the Visual Scene in Driving: An Exploratory Study. Human Factors, 12(1), pp 81 -87

APPENDIX

Procedure for checking luminous intensities

The luminous intensities given for glare control (in Table 6) can not be checked directly, but they can be found by means of a luminance meter measuring the average luminance L_m in a field including the luminaire. This can be seen from the following relation:

$I = L_m \cdot A$ (candela)

where:

L_m is the average luminance of the measuring field
A is the area of the measuring field at the distance s

The accuracy of the method depends on several parameters dealt with in the following, which are available with limited accuracy. Care should be exercised when the results are used.

Method I to determine the area A

For measuring fields extending a small angle α, the area A is found from:

$A = \pi \cdot (s \cdot (\alpha \cdot \pi/ 180)/2)^2 = \pi^3 / 180^2 \cdot s^2 \cdot \alpha^2 = 2{,}39 \cdot 10^{-4} \cdot s^2 \cdot \alpha^2$	(m^2)

where:

s is the distance to the actual light source, in metres
α is the measuring angle of the luminance meter, in degrees

The measuring field of the luminance meter should be as small as possible, but at the same time big enough to include the whole luminaire. The rest of the measuring field should be as dark as possible and absolutely not include other light sources. Normally the accuracy of the specification of measuring field is not a concern, and consequently the accuracy of this method to determine the area of the measuring field is generally unknown.

Method II to determine the area A

If a light source with known luminous intensity I_{normal} is available (this is most often not the case), the area A_{cal} at the actual distance s_{cal} between the light source and the luminance meter can be found from:

$A_{cal} = I_{normal} / L$	(m^2)

where:

I_{normal} is the luminous intensity of the light source (cd)
L is the measured average luminance at the distance s_{cal} (cd/m^2)

resulting in:

$A = (s / s_{cal})^2 * A_{cal}$	(m^2)

Distance measurements

Distances must be measured to be able to determine the size of the measurement field A as well as the actual angles. The use of tape measure is time consuming, but laser based instruments are available for accurate measurement up to distances of approx. 200 metres when retro reflectors are placed at the measuring object. Without retro reflectors the limit is approx. 70 metres. Laser based instruments are ideal for measuring the mounting heights of luminaires.

Angle calculations

The angle γ in Table 6 is found from the measured distances s and h:

$\gamma = \text{atan}(s / h)$	(degrees)

For practical reasons only angles up to approx. 80 degrees can be found. Otherwise the measuring distance will be too long.