Road works during night

Recommendations for the visual environment

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Foreword

This report is the final summary report of a joint Nordic project "*Störande ljus vid vägarbeten om natten*" (*Disturbing lights at road works during night time*) carried out during 2005–2008. The project was commissioned by NordFoU and financed by the Swedish, Danish, Norwegian and Finnish Road Administrations. The Swedish Road Administration has had the overall responsibility for the project. Project manager has been Anita Ihs, VTI. The management group during the last period of the project has consisted of Eva Liljegren (Vägverket), Erik Randrup (Vejdirektoratet), Pål Hauge (Vegdirektoratet) and Tuomas Österman (Tiehallinto). The working group has consisted of Anita Ihs (VTI), Niclas Camarstrand (Vägverket), Kai Sørensen (DELTA), Arve Augdal (SINTEF), Esko Tuhola (Tiehallinto), Antti Tiensuu (LiCon-AT Oy).

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Summary

Road-works almost always mean a restriction of the space available for the road users and thereby also a reduction of the passability. The passage of road-works is a complicated situation for the driver and therefore poses high demands on the traffic controls used (signs, channelling devices, etc.).

To avoid disturbances in dense traffic during daytime road works are to an increasing extent carried out during hours at night when traffic volumes are lower. The requirements on the traffic controls are however considerably different during daylight than during night to provide acceptable visual conditions for the road users.

A considerable difficulty for the driver who is passing the work zone in the dark is to obtain a visual impression of sufficient quality despite glare from meeting traffic, yellow flashing lights, and work zone illumination. This is required to get a correct comprehension on which speed to hold and where to place the vehicle when passing the work zone.

Within NordFoU it was decided to carry out a joint Nordic project to investigate how to provide a good visual environment at night time road works and as a part of this how to best avoid/reduce the adverse effects of glare.

The primary aim of the project was that it should result in recommendations as bases for the improvement and coordination of existing regulations in the Nordic countries by giving

- proposals regarding glare limitation
- proposals for requirements for yellow warning/flashing lights
- proposals for requirements on work zone illumination both with regard to the needs of the road workers and to avoid the glare of drivers
- recommendations regarding specular reflection on wet road surfaces.

Some of the findings in the project are shortly summarised below.

Proposals for glare control

To counteract glare effects road work places should be illuminated. This will increase the adaptation luminance level as well as provide the drivers with a better understanding of the driving tasks.

When conditions are suitable a temporary road lighting installation should be mounted or – if a road lighting installation is planned – this installation should be mounted as early as possible. The luminance level should be at least 0.7 cd/m^2 and the threshold increment maximum 15%.

The proposed requirements to lighting equipment for work site lighting are presented in Table 1 below. The requirements are expressed in terms of classes BB1, BB2 and BB3 of maximum allowable luminous intensities. The requirements apply for each luminaire in the actual orientation in which it is mounted.

The requirements are so adjusted that for luminaires with a mounting height of 7 metres the threshold increment TI will be less than 15% for class BB1, less than 20% for class BB2 and less than 30% for class BB3.

Table 1: Classes BB of luminous intensity for luminaires for recommended glare control.

Class	Maximum permitted luminous intensity (cd)			Other requirements
	$\gamma = 70^\circ$ [1])	$\gamma = 80^\circ$ [1])	$\gamma = 90^\circ$ [1])	
BB1	2500	2000	100	Luminous intensities over 90° should be less than 20 cd
BB2	3300	2700	200	Luminous intensities over 95° should be less than 20 cd
BB3	5000	4500	300	Luminous intensities over 95° should be less than 30 cd
1) Applies for angles γ between the nadir and the direction of view when the luminaire is in its actual orientation and is viewed from the motorist's position.				

Drivers of passenger cars are believed to be that group of motorists who are most severely affected by the light from opposing traffic. One situation where excessive glare can occur is for example at a chicane. In this case it is suggested to use anti-glare screens. These should cover heights from 60 to 120 cm above the road surface, and preferably even higher.

Proposals for yellow flashing lights

The luminous intensity of a flashing light should be in proportion to the square of the distance at which the flashing light is to act. This distance, on the other hand, is related to the driving speed at the location, where the flashing light is to be used.

The relevant distances might be covered by a range from 50 m to 200 m. The shorter distance might be relevant for a city road with a driving speed of 50 km/h and the longer distance for a motorway with a high driving speed. Local speed reductions at road works must be taken into consideration.

Flashing lights for use at long distance must furthermore have a powerful, but narrow beam, while flashing lights for use at shorter distances can have a weaker, but also broader beam.

The preferable luminous intensities for different ambient light conditions and action distances are presented in Table 2 below.

Table 2: Preferable luminous intensities of flashing lights.

Ambient light measured by the illuminance on the horizontal plane (lx)	action distance of the flashing light				
	50 m	71 m	100 m	141 m	200 m
	preferable luminous intensity (cd)				
0,4 lx (darkness)	25	50	100	200	400
4 lx (weak road lighting)	50	100	200	400	800
40 lx (strong road lighting/dusk)	100	200	400	800	1600
400 lx (twilight)	200	400	800	1600	3200
4 000 lx (weak daylight)	400	800	1600	3200	6400
40 000 lx (sunshine)	800	1600	3200	6400	12800

Regulation of yellow flashing lights is traditionally done in two levels. These two levels cannot meet the above given minimum and maximum requirements.

As flashing lights based on LEDs (light emitting diodes) are becoming more common the possibility of regulation in several steps is also introduced.

Proposals for work zone lighting

For work zone lighting symmetrical floodlights without glare shields or limiters should only be used if the angle of tilt is less than 30°, in other words, when using relatively high lighting masts. In this case the problem is however obtaining sufficient light on vertical surfaces, for example, walls, which are often the actual target of the work.

It was found that it is often preferable that lighting is implemented with floodlights that have an asymmetrical light distribution. This will help to avoid causing disturbing light in the environment and also prevent glare without separate grates or limiters.

To ensure proper lighting levels in accordance with the tasks to be performed and also to ensure that glare control is provided it is recommended that a worksite lighting plan is established.

The contents of the worksite lighting plan should cover:

- Description of the target level of lighting in different parts of the workplace in accordance with progress and work phases of the workplace.
- The types, numbers and location of luminaires and lamps.
- The types and number of local/area luminaires.
- Future permanent lighting that may already be taken into use during the construction phase.
- Utilisation/importance of the use of existing, for example, road lighting as worksite lighting.
- Description of the effects that glare caused by worksite lighting might have on traffic and measures needed to prevent these effects.
- Electricity network for lighting.

1 Introduction

Road-works almost always mean a restriction of the space available for the road users and thereby also a reduction of the passability. The passage of road-works is a complicated situation for the driver and therefore poses high demands on the traffic controls used (signs, channelling devices, etc).

To avoid disturbances in dense traffic during daytime road works are to an increasing extent carried out during hours at night when traffic volumes are lower. The requirements on the traffic controls are however considerably different during daylight than during night to provide acceptable visual conditions for the road users.

A considerable difficulty for the driver who is passing the work zone in the dark is to obtain a visual impression of sufficient quality despite glare from meeting traffic, yellow flashing lights, and work zone illumination. This is required to get a correct comprehension on which speed to hold and where to place the vehicle when passing the work zone.

In order for the driver to manage this task it is required that the traffic controls used at the road works can not be misinterpreted. Another prerequisite is that the visual conditions are good. The latter implies among other things that the total glare must be limited and also that the illumination is of sufficient quality on the sections along the work zone that impose particularly high demands on the driver.

During night-time the pavements are also often wet or damp, particularly during the period from October to March, which increases the pavements reflectivity. This means that the light from yellow flashing lights, vehicles headlights and other light sources will hit the eyes of the driver directly as well as indirectly by reflection in the wet surface. The reflections may conceal road markings, add to the glare and increase the complexity of the visual information to the driver.

This constitutes not only a safety risk for the driver passing the work zone but also for the workers within the work zone. There is a potential risk that a driver misconstrues/misjudges the information from the traffic controls and drives into the work zone.

Within NordFOU it was decided to carry out a joint Nordic project to investigate how to provide a good visual environment at night time road works and as a part of this how to best avoid/reduce the adverse effects of glare.

2 Objectives

The overall objectives of the project have been to improve safety for both the drivers who are to pass a work zone when it is dark and for the people working within the work zone, and in particular concerning road works at night on major roads.

In particular, the safety, but also the accessibility and the comfort, is increased for the drivers through improved visual guidance. An improved visual guidance for the drivers that allows the road works site to be passed in a safe manner also means increased safety for the people who are working within the work zone. The risk that drivers misinterpret the traffic controls (signs, warning lights, etc.) is reduced and hence the risk that drivers run into the work zone is also reduced.

Within the project the disturbing glare from the different elements – yellow flashing lights, headlights, work zone illumination, etc. – have been investigated separately and in combination.

The aim of the project was that it should result in recommendations as bases for the improvement and coordination of existing regulations in the Nordic countries by giving

- proposals regarding glare limitation
- proposals for requirements for yellow warning/flashing lights
- proposals for requirements on work zone illumination both with regard to the needs of the road workers and to avoid the glare of drivers
- recommendations regarding specular reflection on wet road surfaces
- proposals for requirements/recommendations for other traffic control devices (e.g. signs).

3 Project organisation and studies

The Swedish Road Administration was appointed by NORDFOU to be responsible for the management of the project. The SRA commissioned a researcher from VTI to be the operative project manager.

The Management group consisted of one representative from each participating road administration, i.e. one from Sweden, Denmark, Norway and Finland, respectively.

The Working group consisted of one or two consultants/researchers from each participating country. These were from SINTEF, Norway, DELTA, Denmark and LiCon-AT OY, Finland.

Four separate preliminary studies were carried out in the first stage of the project concerning

- methods to describe glare
- yellow warning/flashing lights,
- work zone illumination (a literature survey),
- specular reflection in wet road surfaces.

The results from these studies were used as bases for the planning of a number of pilot studies and are also referred to in Chapters 4, 5, 6, and 7, respectively.

The work zone illumination has been further studied in separate field tests in Finland (Chapter 6).

The first pilot study was carried out on an airfield outside Copenhagen, Denmark, where a work zone was built up on a runway (see Chapter 5). Two types of work zone illumination and a number of different variants of running lights (brightness, frequency, sequence, etc.) were tested. All assessments were made by a panel of experts consisting of the members of the project team, who were standing on a fixed distance from the work zone.

A second pilot study was carried out on a real 2+1 road outside Linköping, Sweden, where a stationary work zone was established on the single lane part of the road. The pilot study included driving tests where the test subjects (drivers) were persons older than 50 years. In this way a more realistic situation was obtained where the assessments were done when the test subjects drove past the work zone. The test subjects had to answer a questionnaire, and the speed of their vehicles as well as the speed of the ordinary traffic passing the work zone was also registered.

Four variants of yellow running lights were tested. The three variants that were considered the best in the first pilot and a fourth variant with short intensive flash which was expected to be experienced as worse due to bad visual guidance. For more details, refer to (Ihs et al., VTI notat 25-2008)

In the final stage of the project an expert group made evaluations of temporary traffic controls for a stationary motorway road works that was set up on a closed part of E6 outside Varberg (see Chapter 8). The expert group consisted of 10 persons, most of them coming from the project group.

In this case a number of different scenarios, i.e. different combinations of traffic control components, were assessed by the experts while driving past the work zone. The experts made a subjective evaluation of the degree of glare as well as the visual guidance.

4 Glare at road work sites

4.1 Introduction

To carry out road works effectively, road works are more and more often carried out during night-time. This implicates rerouting of the traffic to road conditions that are unknown and unusual to the motorist. Driving during dark hours can be demanding, and the conditions at road works represent a challenge to the drivers. Therefore, it is important to provide adequate visual conditions for safe driving.

Glare may be caused by temporarily installed work lighting luminaires at the construction site, yellow flashing warning lights or by headlights and warning lights on work vehicles. Additional glare is caused by low beam headlights on vehicles. These are designed in view of a compromise between the driver's need for illumination of the road and the need to restrict glare to other drivers. But this compromise may not work for the unusual conditions at road work places, where the road illumination may be less good and the glare may be more severe.

This chapter addresses only disability glare, which reduces the drivers ability to see as well as without glare. Concerning another type of glare called discomfort glare, refer to "Störande ljus vid vägarbeten om natten. Delprosjekt synsnedsettende blending" (in Norwegian) by Arve Augdal, 9 August 2008.

Methods to describe glare are provided in 4.2, while practical methods for the determination of glare are provided in 4.3.

The methods for the determination of glare have been used in full scale tests carried out as a part of the project. The methods have thereby been tested and have also provided useful information about glare caused by work lighting. Refer to "Störande ljus vid vägarbeten om natten. Delprosjekt synsnedsettende blending" (in Norwegian) by Arve Augdal, 9 August 2008 for an account of these tests.

Glare caused by cars in meeting situations constantly change as the cars change mutual locations. Because of this, this source of glare had been studied by means of simulations of meeting situations. This is accounted for in 4.4, which also provides considerations for anti-glare screens.

Finally, proposed recommendations for glare control at road work places are provided in 4.5.

4.2 Methods to describe glare

The disability glare is physiological and describes a negative influence on the visual conditions. Light from a (glaring) light source is scattered by the 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'.

4.2.1 Equivalent veiling luminance

The equivalent veiling luminance L_v caused by one light source is found by the so-called Stiles-Holladays glare formula for point sources:

$L_v = K \times E_{bl} / \theta^2$	(cd/m^2)	equation 1

Where	K	is a factor with 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 (°)
And	E_{bl}	is the illuminance caused by the light source on a plane perpendicular to the direction of view, just in front of the observer's eyes (lux).

Equation 1 is valid for θ in the range of $1° \leq \theta \leq 30°$. The angle θ is illustrated in figure 4.1.

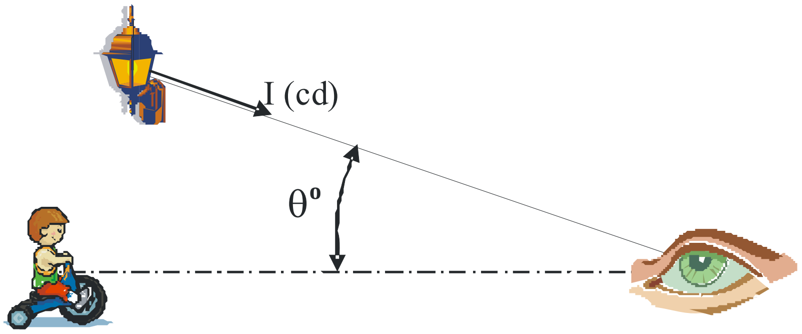

Figure 4.1: The angle θ in the disability glare equation.

E_{bl} is calculated from:

$E_{bl} = \frac{I}{d^2} \times \cos\theta$	(lux)	equation 2

Where	I	is the luminous intensity of the glare source against the eyes of the observer (cd)
and	d	is the distance to the glare source.

The amount of stray light in the eye increases by the age. For the average person, CIE recommends that the factor K is calculated from the so-called age adjusted Stiles-Holladays formula:

$K = 10 \times \left(1 + \left(\frac{A}{70} \right)^4 \right)$		*equation 3*

where	A	is the age of the observer (years).

Refer to CIE 146:2002 regarding the factor K.

EXAMPLE: Compared to the value of K for a young person of 10, the value is approximately 10% higher for a person 40 years of age and 100% higher for a person 70 years of age.

In practical circumstances there is mostly more than one light source that contributes to the veiling luminance. This can for instance be several luminaires of a road lighting installation. The individual contributions can be calculated according to equation 1 and summed up to provide the total veiling luminance:

$L_v = K \times \Sigma(E_{bl,i} / \theta_i^2)$	(cd/m^2)	equation 4

where	Σ	means summation for light sources in the field of view
and	$E_{bl,i}$ and θ_i	are individual values of E_{bl} and θ for the light sources.

4.2.2 Threshold increment as a measure of disability glare

The veiling luminance has to be put into relationship to the adaptation level of the observer in order to obtain a measure of the severity of the disability glare that it causes.

In road lighting and other types of outdoor lighting a rather complex measure of the seriousness of the glare is in use. This measure is the threshold increment TI, which describes the percentage that the contrast between an object and its background has to be increased for the object to be as visible with glare as it would have been without glare. TI is determined from:

$TI = L_v / L^{0,8}$	(%)	equation 5

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

Equation 5 is valid for L in the range of 0.05 cd/m^2 < L < 5 cd/m^2, which is sufficient for use in road lighting and in most other night-time applications. In road lighting, the adaptation luminance is assumed to be equal to the average road surface luminance. CIE states that TI values lower than 2% can be neglected, refer to CIE 31:1976. Further more CIE recommends that TI values for road lighting installations should be lower than 10% and never higher than 15%, refer to CIE 115:1995.

An early proposal for glare limitation for light sources and lighting installations external to roads is found in ”Mörkertrafik rapport nr. 1, Bländing från belysningsanläggningar vid sidan av vägan” (in Swedish with a summary in English).

These glare limitations are expressed by means of maximum limits for the equivalent veiling luminance at some levels of road lighting. These, on the other hand, may be transformed to maximum limits for the TI. Table 4.1 shows both sets of maximum limits.

It can be observed that the above-mentioned CIE recommendations are more permissible than the recommendations in "Mörkertrafik rapport nr. 1".

Table 4.1: Glare limitation for light sources and lighting installations external to roads (Mörkertrafik rapport nr. 1).

Road lighting condition	Average road surface luminance	Maximum value of the equivalent veiling luminance L_v	Maximum value of the threshold increment TI
Unlit road	-	0.050 cd/m^2	not applicable
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%

4.2.3 Visual search when driving and its influence on the adaptation luminance

While the adaptation luminance is generally assumed to be equal to the average road surface luminance on roads with road lighting, there is no recognised method to determine the adaptation luminance when driving on unlit roads.

However, 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 reported in the literature show how drivers search the visual field when they are driving during daytime. Examples of this type of results from Mourant, R.R., Rockwell, T.H. ”Mapping eye-movement patterns to the visual scene in driving: An exploratory study” are shown in figures 4.2 and 4.3.

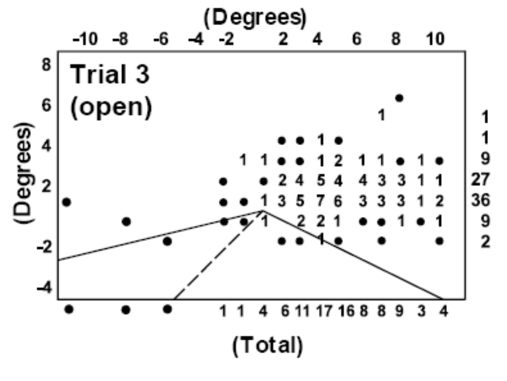

Figure 4.2: Example of visual search on an open road.

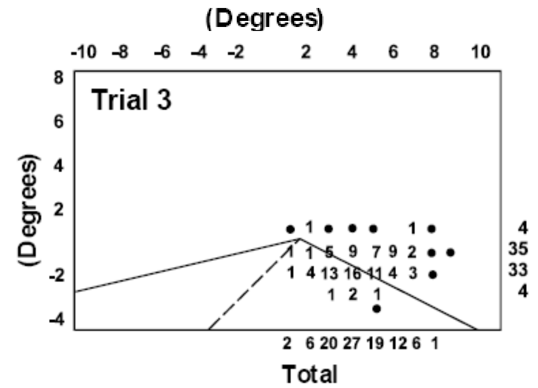

Figure 4.3: Example of visual search when following a car.

Figures 4.2 and 4.3 show the road with its limitations and the centre line as 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 an influence on the search pattern. It can also be seen that the longest search 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 quite the same way when driving on unlit roads at night, especially when the low beam is used. But it is reasonable to assume that the search concentrates on locations on the road that are far ahead. This is where the road surface luminance is low due to the cut-off of the low beam. Additionally, the surroundings to the road remain dark as they receive very little illumination.

Some luminance values were measured during full scale tests carried out as a part of this project. These values suggest that the adaptation luminance is approximately 1 cd/m^2 when driving with the low beam on dry roads, and clearly less than 1 cd/m^2 when driving with the low beam on wet roads. When driving next to areas with outdoor work place lighting, the adaptation luminance may be above 1 cd/m^2 due to spill light from the work place lighting installation. For more details, refer to the report ” Störande ljus vid vägarbeten om natten. Delprosjekt synsnedsettende blending” (in Norwegian) by Arve Augdal, 9 August 2008.

4.3 Practical methods for glare control

Measures of glare such as the equivalent veiling luminance and the threshold increment can be calculated when photometric data for the light sources and the luminaires and the relevant data for the geometrical situation are available. The calculations are of the same nature as those that are carried out during the design of road lighting installations and other outdoor lighting installations and are based on the equations given above. However, these data will in general not be available for work place lighting at work zones.

It could then be considered to measure the individual parameters of the equations on location by means of portable instruments before applying the equations.

However, this is not possible. In the case of the illuminance E_{bl}, which is a central parameter, the illuminance values are too small, the individual contributions from different glare sources are difficult to separate from each other, and this would be a large job in any case.

Therefore, a novel method has been designed for the measurement of disability glare. This method is based on equations 1 and 4 and is described in the following.

4.3.1 How to determine the equivalent veiling luminance from field measurements

This method includes two steps. At first the illuminance E_{bl} from each of the glare sources is measured. Then the angle θ between the direction of view and the direction towards the glare source is determined.

4.3.2 Illuminance measurements by the use of a luminance meter

It is necessary that the contribution from each of the glare sources is measured independently, refer to equation 4.

It is practically impossible to do these measurements by the use of a conventional illuminance meter. The reasons are that such an instrument receives light from the full hemisphere in front of the illuminance detector and cannot separate contributions from different glare sources. Additionally, portable illuminance meters are not designed to cope with the very low illuminances that would have to be measured.

One could imagine that an illuminance meter is provided with a long, narrow tube to reduce the angular space that contributes to the instrument reading. However, this approach is not feasible for lack of a viewfinder.

The instrument that is needed is really a luminance meter, as a luminance meter has a narrow reduction of the angular space to a measured field of diameter 1 or less, a viewfinder and a much higher sensitivity than an illuminance meter (because the light from a large lens is focussed onto a small detector in the luminance meter).

It is important to understand that a luminance meter can work as an illuminance meter after recalibration. A proof of this and a description of the recalibration method is given in the report ”Disturbing light at road work places - disability glare” by Arve Augdal, 9 August 2008.

4.3.3 Determination of the angle to the glare source

The angle θ to the glare source can be determined by the use of an angle meter supplied with aiming devices. But the most practical way is to determine the angles from a photograph, which makes it possible to determine the angle to any point at any time, and 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 angles 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 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 is calculated from:

$m = b_{cal} / d$	equation 6

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:

$\theta = \tan^{-1}(b_{mea} /(s \times m))$	(°)	equation 7

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 and b_{mea} should all be measured by the same units.

4.3.4 Calculation of the equivalent veiling luminance

When the illuminance E_{lum} (just in front of the luminance meter on a plane perpendicular to the direction from the luminance meter to the glare source) has been determined using the reading from the luminance meter, and the angle θ between the direction of view and the direction to the glare source is determined photographically using equation 7, the equivalent veiling luminance is determined from:

$L_v = K \times E_{lum} \times \cos\theta / \theta^2$	(cd/m^2)	equation 8

4.4 Glare caused by cars in meeting situations

4.4.1 Simulations of 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, downloaded from http://www.reflectives.averydennison.com/films_ergo2001.html. This program is specially developed for the use in situations with retro reflective signs, but intermediate results offer the possibility to use the program for glare calculations as well.

A database with photometric data for different types of headlamps 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 a European low beam headlamp as defined in a preliminary report from CIE TC 4-20 from 1993 is used in the simulations.

A four lane motorway where the two driving directions are separated by a central reserve is used as an example. The situations are shown in figure 4.4. A car X in a chicane marked ⊗ causes glare to opposing traffic represented by a car Y. The driving direction of car X is indicated by red arrows, while a green arrow is used for the driving direction of car Y.

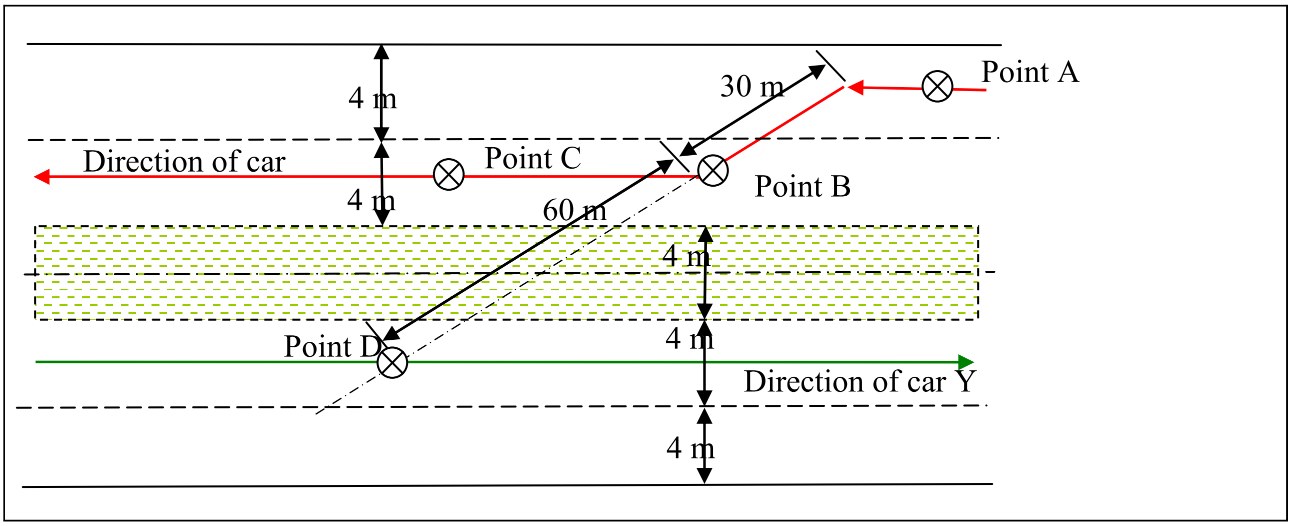

Figure 4.4: Situations used for the calculation of disability glare.

Three situations are considered:

- car X is in its the outermost lane indicated by point A
- car X is at the end of the chicane indicated by point B
- car X is in its left driving lane indicated by point C.

The results of the glare calculations in terms of threshold increment TI are provided in figures 4.5, 4.6 and 4.7 for the three situations respectively. In each case, TI values are provided for a range of distances between the two cars, and for different assumptions regarding the adaptation luminance in the range from 0.2 to 1.2 cd/m^2.

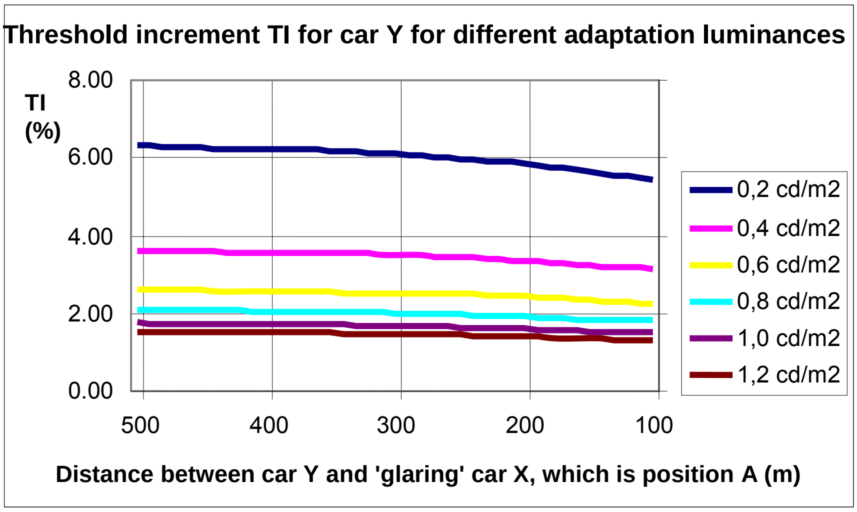

Figure 4.5: Threshold increment when car X is in its right driving lane.

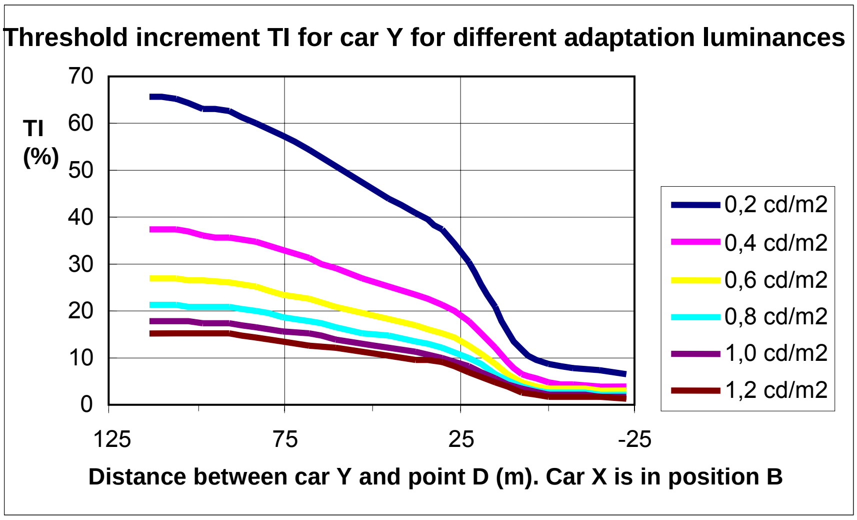

Figure 4.6: Threshold increment when car X has reached the end of the chicane.

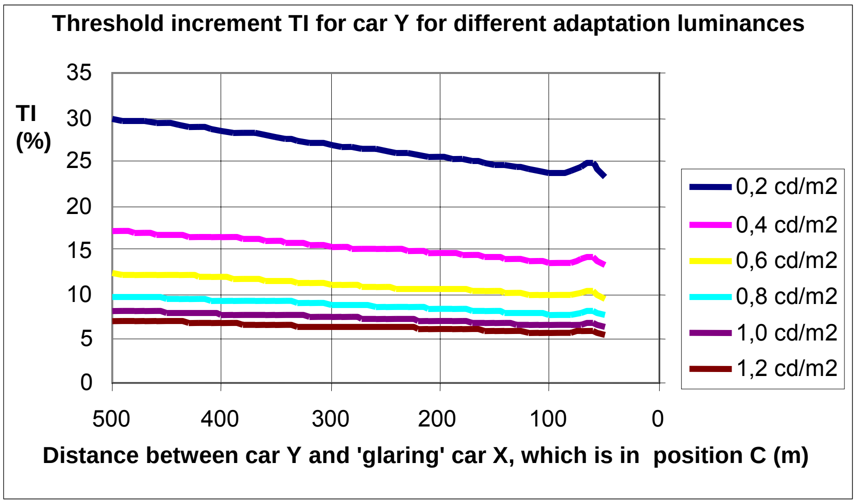

Figure 4.7: Threshold increment when car X is in its left driving lane.

Please observe that different scales are used on the ordinate axes of figures 4.5, 4.6 and 4.7.

Figures 4.5 and 4.7 relate to situations, where the two cars drive in opposite directions with a fixed transverse separation.

Both figures show that TI values change only slowly with the distance between the two cars. This means that two cars at for instance 200 and 300 m distance are equally glaring and accordingly that glare is higher when there is more than one opposing car.

The transverse separations are different for the two situations, and the figures show that the TI values are higher for the smallest separation (higher in figure 4.7 than in figure 4.5).

Those situations are similar to normal meeting situations on two-lane roads, where the lateral distance is much smaller than in the two above-mentioned situations. Most drivers are familiar with the strong glare in such situations, in particular when meeting several vehicles simultaneously.

Figure 4.6, on the other hand, relates to a situation, where car X moves at an intersecting course to car Y, so that car Y passes through the elevated part of the low beam headlamps of car X. This causes very high TI values for the driver of car Y during some of the ride. It is evident that this situation is the most difficult of the three. For such situations in particular it should be considered to take steps to reduce the glare.

It should be noted that the headlamp data used for the simulations are based on new, clean and perfectly aimed headlamps. Worn and dirty headlamps provide more scattered light and thereby higher glare levels. Misaimed headlamps can be particularly glaring levels. If windscreens are dirty or wet, this in itself adds a veil with an effect similar to glare.

The simulations relate to situations where only two cars are involved and it has already been pointed out that glare is higher when there is more than one opposing car. In real traffic, a row of meeting cars may be encountered. Glare in practical traffic is anticipated to be far more severe than what the results from these calculations show.

4.4.2 Screens between the driving directions

One possible anti-glare measure is to mount anti-glare screens between cars with opposing driving directions. For a screen to be effective, it has to prevent direct view to the headlamps of opposing cars.

In order to serve for drivers of passenger cars, the screen should cover heights from 65 cm to 120 cm, refer to figure 4.8. To serve adequately for somewhat larger vehicles, the screen should be somewhat higher. Such screens could be designed to be integrated into safety barriers.

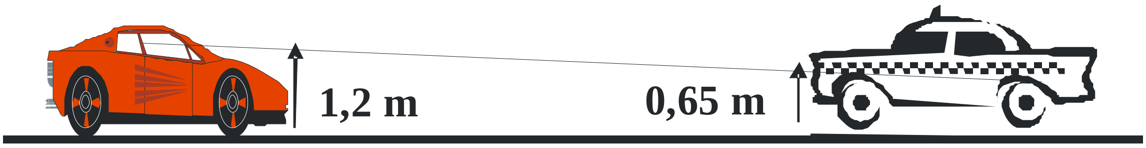

Figure 4.8: Screen heights that are necessary for normal passenger cars.

For large vehicles the screens must be even higher, but the situation for the drivers of these types of vehicles is not critical as they are sitting higher so that the angle between the direction of view and the direction to the glaring headlights is larger. This in itself reduced glare considerably.

An example of an anti-glare screen is shown in figure 4.9. Its dimensions are not entirely adequate, but even so the use of such a screen would be useful.

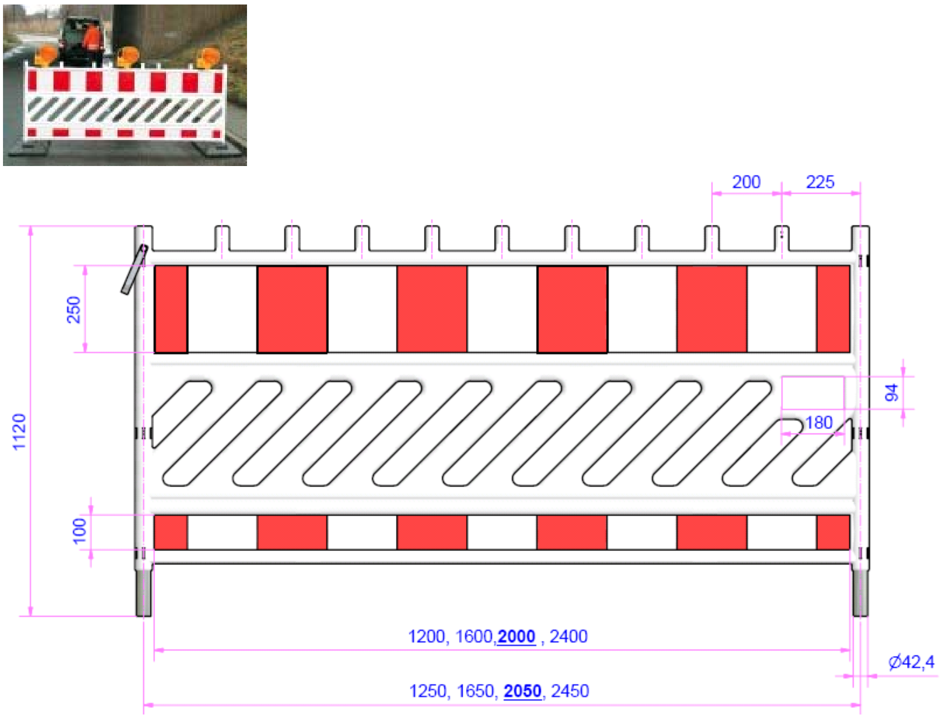

Figure 4.9: Safety barrier and light screen (not optimal) (Adolf Nissen Elektrobau GmbH + Co. KG, Tönning, Germany)

4.5 Proposed recommendations for glare control

4.5.1 Illumination of road work places

Road work places should be illuminated. This will counteract glare effects by increasing the adaptation luminance level as well as providing the drivers with a better understanding of the driving tasks.

When conditions are suitable a temporary road lighting installation should be mounted or – if a road lighting installation is planned – this installation should be mounted as early as possible. The luminance level should be at least 0.7 cd/m^2 and the threshold increment maximum 15%.

4.5.2 Requirements to lighting equipment for work place lighting

The requirements as provided in table 4.2 are expressed in terms of classes BB1, BB2 and BB3 of maximum permissible luminous intensities. The requirements apply for each luminaire in the actual orientation in which it is mounted. For the orientation, in which a luminaire is normally to be used, the luminaire should comply with the requirements of classes BB1 or BB2.

The luminous intensities are absolute values (cd) instead of values relative to the luminous flux of the light source (cd per 1000 lm) as often used in similar cases. This provides the advantage that compliance with the requirements can be tested for already installed luminaires, if not already secured by the choice of suitable luminaires at the design stage.

Regarding a test method for already installed luminaires, refer to the report ”Störande ljus vid vägarbeten om natten. Delprosjekt synsnedsettende blending” (in Norwegian) by Arve Augdal, 9 August 2008. The choice of suitable luminaires during the design stage should be based on photometric data obtained in laboratory measurements.

The requirements are so adjusted that for luminaires with a mounting height of 7 metres the threshold increment TI will be less than 15 % for class BB1, less than 20 % for class BB2 and less than 30 % for class BB3.

Table 4.2: Classes BB of luminous intensity for luminaires, for recommended glare control.

Class	Maximum permitted luminous intensity (cd)			Other requirements
	γ = 70° 1)	γ = 80° 1)	γ = 90° 1)	
BB1	2500	2000	100	Luminous intensities over 90° should be less than 20 cd
BB2	3300	2700	200	Luminous intensities over 95° should be less than 20 cd
BB3	5000	4500	300	Luminous intensities over 95° should be less than 30 cd

2) Applies for angles γ between the nadir and the direction of view when the luminaire is in its actual orientation and is viewed from the motorist’s position.

Additionally, glare is well controlled if the luminaire has a plane aperture covered by flat glass, which is tilted maximum 5 degrees towards the traffic. The mounting height should not be less than 6 metres.

4.5.3 Anti-glare screens

In situations where excessive glare can otherwise occur, such as at a chicane, anti-glare screens should be used. Anti-glare screens should cover heights from 60 cm to 120 cm above the road surface, and preferably even higher.

4.6 Literature

CIE 31:1976. ”Glare and Uniformity in Road Lighting Installations”

CIE 147:2002. ”CIE Collection on Glare”

CIE 115:1995. ”Recommendations for the Lighting of Roads for Motor and Pedestrian Traffic”

Mörkertrafik rapport nr. 1. ”Bländing från belysningsanläggningar vid sidan av vägen” (1977)

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

Ergo2001.Copyright 1991 – 2001 by Avery Dennison http://www.reflectives.averydennison.com/films_ergo2001.html

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

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

”Störande ljus vid vägarbeten om natten. Delprosjekt synsnedsettende blending” (in Norwegian) by Arve Augdal, 9 August 2008

5 Yellow flashing lights

5.1 Introduction

Yellow flashing lights have a number of applications at road works including pre-warning lights, attention lights on road signs and cross booms, sequential running lights, and flashing arrows and crosses on work vehicles.

Yellow flashing lights need to be clearly visible and to create attention without causing disturbing effects like glare and reflections in wet road surfaces to an unnecessary degree. It is an advantage that yellow flashing lights can be located visually so that drivers can use them for general orientation.

It is generally assumed that the visibility, attention effect and disturbing effects of yellow flashing lights depend on their effective luminous intensities, the distances at which they are to act and on ambient light levels.

Additionally, it is generally assumed that the effective luminous intensity depends on the duration of the flash, and that the duration also plays a role for the visual location of yellow flashing lights.

EN 12352 ”Traffic control equipment - Warning and safety light devices” requests that the effective luminous intensity shall be calculated by means of Blondell-Rey’s equation, it defines classes of yellow flashing lights by means of requirements for luminous intensities and angular beam dimensions and defines some other classes for other properties.

These classes seem to reflect a selection of products on the market and not the need for luminous intensities for specific applications. EN 12352 does not provide practical guidance regarding applications of yellow flashing lights.

The project described in this chapter aims to clarify the following questions:

a. how the need for luminous intensities depends on the distance

b. how the need for luminous intensities depends on the ambient light in the range from dark night surroundings over conditions with work lighting or road lighting to dusk, twilight and different daylight levels

c. how the duration of the flash and the use of a steady background light influences the perception of yellow flashing lights

d. if there are special conditions regarding the different applications of yellow flashing lights.

For use in the project, five experimental flashing lights were produced at DELTA. These are described in 5.2.

The five experimental flashing lights have been used in all of the evaluations discussed in the following except those concerning a yellow flashing arrow mentioned in 5.4.2. This yellow flashing arrow was made available by Multi Afspærring ApS.

Initial evaluations concerning items a, b and c were carried out during a project meeting on 16/18 August 2005 by Sara Nygårdhs, Sven-Olof Lundkvist and Behzad Koucheki (all VTI), Ib Lauridsen (previously Frederiksborg county) and Kai Sørensen (DELTA). These evaluations are referred to as ”expert panel” evaluations in the following.

Additional evaluations concerning item b were carried out by persons employed at DELTA.

Further evaluations concerning a pair of yellow flashing light on road signs and a number of lights forming a yellow flashing arrow are relevant for items b and d. These evaluations were also carried out by persons employed at DELTA or connected to DELTA and are reported in more detail in:

- ”Preferable luminous intensity of a pair of yellow flashing lights on road signs” by Kai Sørensen and Torben Holm Pedersen, DELTA, 16 January 2008
- ”Preferable luminous intensity of a yellow flashing arrow” by Kai Sørensen and Torben Holm Pedersen, DELTA, 28 March 2008.

Finally, some evaluations concerning sequential running lights were carried out by the working group for the full project during a pilot project meeting at Værløse airport during March 2006. These evaluations are relevant for items b, c and d and are reported in more detail in:

- ”Evaluations of sequential running lights at Værløse airport” by Kai Sørensen, DELTA and Britta Fismen, SINTEF, 3 April 2006.

Sections 5.3, 5.4, 5.5 and 5.6 provide accounts for the above-mentioned items a, b, c and d. Section 5.7 provides conclusions in the form of a framework for requirements for yellow flashing lights and use of these lights at road works.

An actual proposal for requirements is found in:

- ”Forslag til regler for gule blinklygter” (in Danish) by Kai Sørensen, DELTA, 7 April 2008.

5.2 Yellow flashing lights used in the experiments

The experiments concerns several properties of flashing lights including the luminous intensity, the flash rate, the flash duration, the off period, the use of background light and the coordination between two or more flashing lights.

Therefore, it was felt necessary to produce a number of flashing lights where those properties could be set with relative ease instead of relying on commercially available flashing lights.

The experimental flashing lights were produced at DELTA. They are based on commercially available 20 cm diameter lights in which the lamps and reflectors have been replaced by inserts consisting of 30 powerful yellow LED’s (LUXEON Star/O by Lumiled) and electronic ballasts. The ballasts were designed to accept inputs of:

- a luminous intensity in steps from 0 to 999
- a period (flash duration plus off period) in steps of milliseconds
- a flash duration in steps of milliseconds
- a background signal for the off period in steps from 0 to 999
- a total period for two or more lights in a sequence in steps of milliseconds
- a delay between two or more lights in a sequence in steps of milliseconds
- start of the off period of two or more lights in a sequence either individually after the flash period or simultaneously after the flash period of the last signal in the

sequence (i.e. either the lights go on and off individually in the sequence, or they go on one by one but off simultaneously).

The luminous intensity of an insert reaches approximately 5000 cd with a beam width of approximately ±6°. When equipped with the front glass of the original light, the luminous intensity reaches approximately 2500 cd with a beam width of approximately ±8°.

The luminous intensity is not quite linear with respect to the step, and the different lights do not have quite the same luminous intensity at a given step. However, calibration curves have been determined in laboratory measurements so that a given luminous intensity can be set for each of the lights with or without a front glass.

The flashing lights were used in all cases with the front glass mounted**.**

5.3 The influence of distance

The five experimental yellow flashing lights were placed at distances of 50 m, 71 m, 100 m, 141 m and 200 m from an observation location and set to provide luminous intensities of respectively 100 cd, 200 cd, 400 cd, 800 cd and 1600 cd. The period was set to 1 second (60 per minute) including a flash duration of 0.5 second. Refer to figure 5.1.

At the observation location, the flashing lights all provide the same illuminance of 0.04 lx. An expert panel of 5 observers evaluated the sensation of light created by the flashing lights and all felt confident that the sensation of light was the same for all the flashing lights.

This confirms the assumption that a relatively small light source leads to a sensation of light that is measured by the illuminance at the observer's eyes created by the light source.

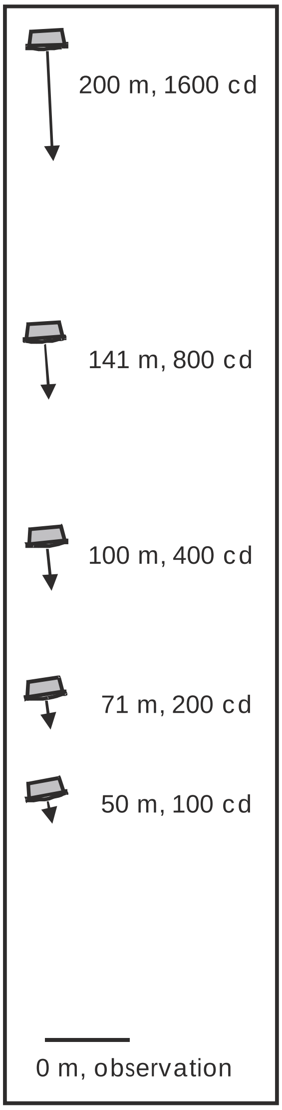

Figure 5.1: Set-up used to confirm the influence of distance.

5.4 The influence of ambient light

5.4.1 Evaluations by the expert panel

The five experimental yellow flashing lights were arranged as shown in 5.2, so that they could be observed from a single location at 50 m distance. The lights were set to provide luminous intensities of respectively 100 cd, 200 cd, 400 cd, 800 cd and 1600 cd with, however, a resetting of the fifth light to 50 cd instead of 1600 cd during the darkest ambient light condition. The period was set to 1 second (60 per minute) including a flash duration of 0,5 second.

NOTE: The luminous intensities are actual intensities and not effective luminous intensities as introduced in 5.5. However, with a flash duration of 0,5 second the difference between actual and effective luminous intensities is small.

The lights were evaluated by the expert panel on the basis of the rather loose criterion that the luminous intensities should make the lights conspicuous without being too glaring. The scale was the following:

1: too weak

2: a bit too weak

3: preferable

4: a bit too strong

5: too strong.

The evaluations were repeated under different ambient conditions ranging from almost darkness to clear sunshine. The ambient light was represented by the illuminance on the horizontal plane.

The evaluations as averages for the expert panel members are shown in figure 5.3.

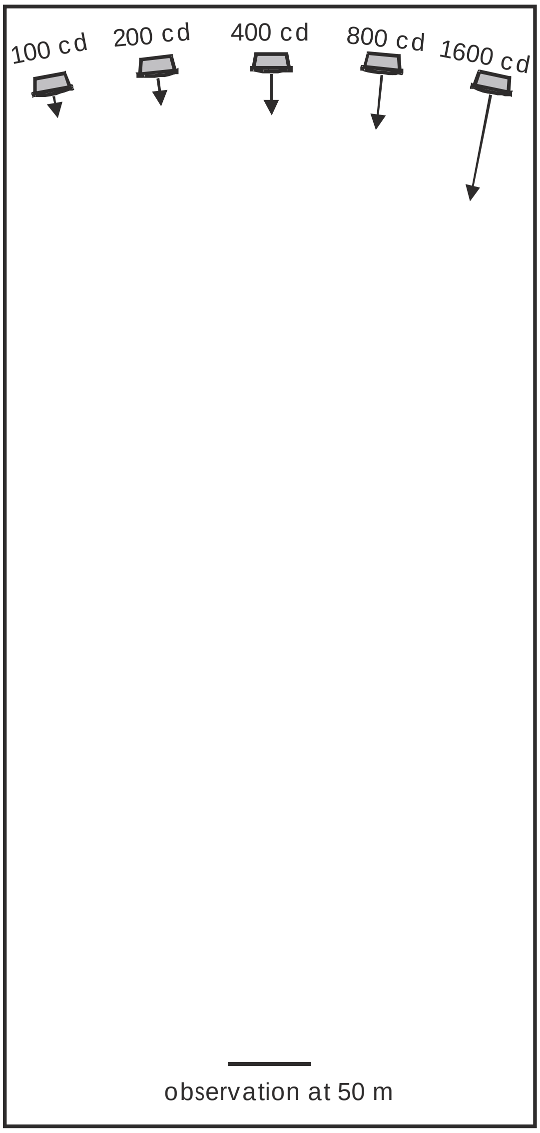

Figure 5.2: Set-up used for the evaluation of the influence of ambient light.

Whenever a curve in figure 5.3 for a luminous intensity (50 cd, 100 cd, 200 cd, 400 cd, 800 cd or 1600 cd) crosses the line for the mark of 3 (preferable), a point is defined by means of the luminous intensity at the horizontal illuminance where the crossing takes place. These points are shown in figure 5.4, where they define a line for the preferable luminous intensity in relation to the horizontal illuminance.

This line has been derived by linear regression, but has been adjusted slightly so that the luminous intensity is 25 cd at an illuminance of 0.4 lx and increases by a factor of 2 when the illuminance increases by a factor of 10.

Similar lines for the average marks of 2 (a bit too weak) and 4 (a bit too strong) are shown in figure 5.4. These are seen to lie respectively 3 times lower and 3 times higher in luminous intensity.

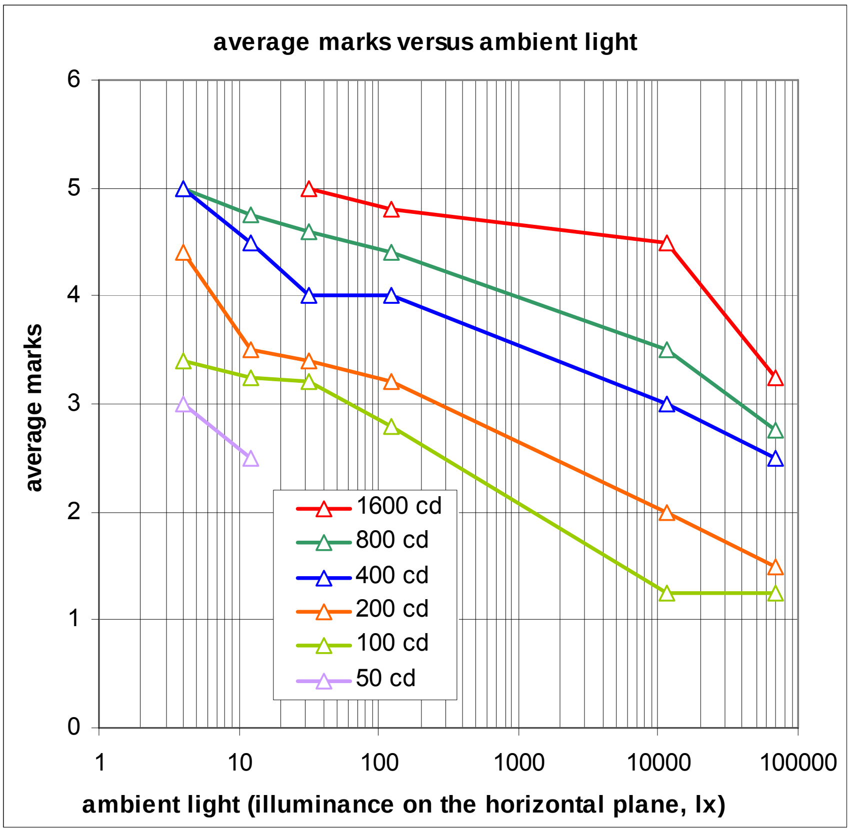

Figure 5.3: Average marks versus ambient light.

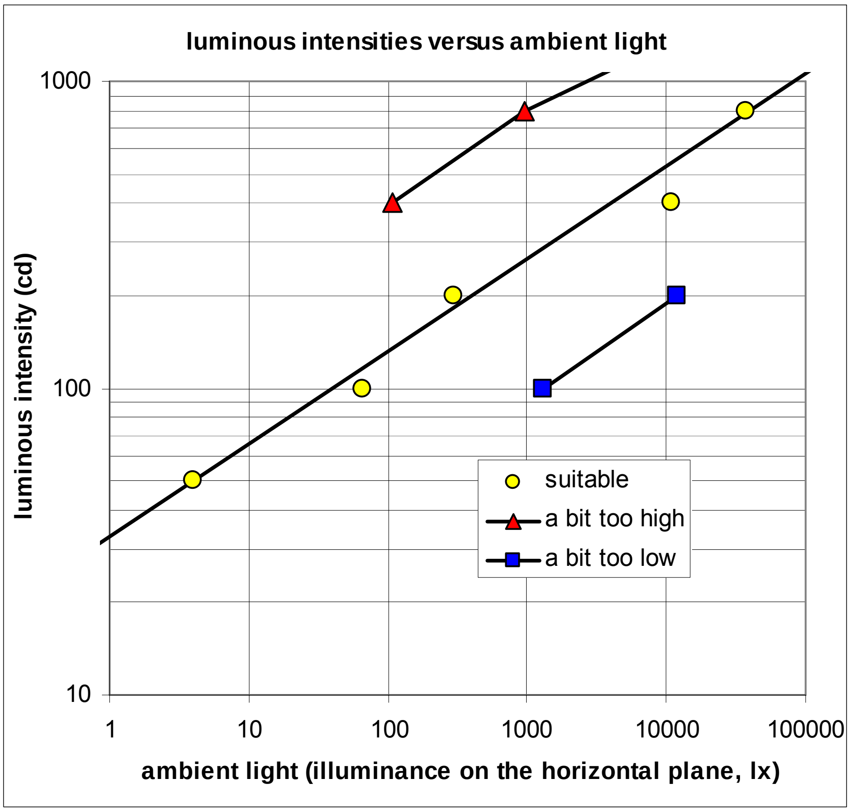

Figure 5.4: Preferable luminous intensity versus ambient light.

5.4.2 Other evaluations

Persons employed at DELTA made evaluations at three occasions during the autumn of 2005 with participation of 30-50 persons on each occasion.

At one of the occasions, the lights were placed in a random order regarding the luminous intensities, and at the other two occasions the lights were placed with luminous intensities in an increasing order from left to right.

The luminous intensities for an average mark of 3 (preferable) are indicated in figure 5.5 together with the results of the expert panel as discussed in 5.4.1.

It can be seen that the ambient light level did not influence the evaluations in a systematic manner, while the order of the luminous intensities seems to have had an influence.

This indicates that the persons were not able to evaluate the lights as if they were placed at a road work, but might have compared the lights to each other or with other familiar lights such as road signals.

It is therefore assumed that these evaluations were affected by the way they were carried out and that the results should be disregarded.

Figure 5.5 includes other results, where persons employed at DELTA or connected to DELTA evaluated lights with luminous intensities displayed one at a time.

These evaluations concerned a pair of yellow flashing lights on road signs and a number of yellow flashing lights forming an arrow. Refer to ”Preferable luminous intensity of a pair of yellow flashing lights on road signs” by Kai Sørensen and Torben Holm Pedersen, DELTA, 16 January 2008 and to “Preferable luminous intensity of a yellow flashing arrow” by Kai Sørensen and Torben Holm Pedersen, DELTA, 28 March 2008. Figure 5.6 shows a situation from the last-mentioned evaluations.

The evaluations were carried out from a car with low beam headlamps during some nights in relatively dark ambient conditions early 2008. The observation distance was 100 m, but results are indicated in figure 5.5 for a distance of 50 m according to 3.3 after multiplication by $(50/100)^2 = 0.25$.

Figure 5.5 further includes the results of some additional evaluations that were carried out by the working group for the project at Værløse airport during March 2006, refer to ”Evaluations of sequential running lights at Værløse airport” by Kai Sørensen, DELTA and Britta Fismen, SINTEF, 3 April 2006. These evaluation concerned yellow flashing lights used as sequential running lights and involved different sequence and flash modes, and both a daytime and the nighttime situation.

NOTE: The results from the pilot project at Værløse are based on effective luminous intensities as introduced in 5.5. The other results are based on actual luminous intensities during the flash, but with a flash duration of 0.5 second which makes the difference between actual and effective luminous intensities small. Refer to 5.5.

The additional results are in reasonable agreement with the results by the expert panel pointing, however, to somewhat lower luminous intensities. This is assumed to confirm the results by the expert panel, but also to indicate that the simultaneous use of two or more yellow flashing lights leads to a slight reduction of the preferred luminous intensity as compared to the use of a single flashing light. However, as measured on the mark scale or as compared to the variation from person to person, the reduction is small.

The evaluation of pair of yellow flashing lights on road signs involved road signs with different levels of retroreflection. There was a weak trend that a higher level of retroreflection leads to a slightly higher preferred luminous intensity.

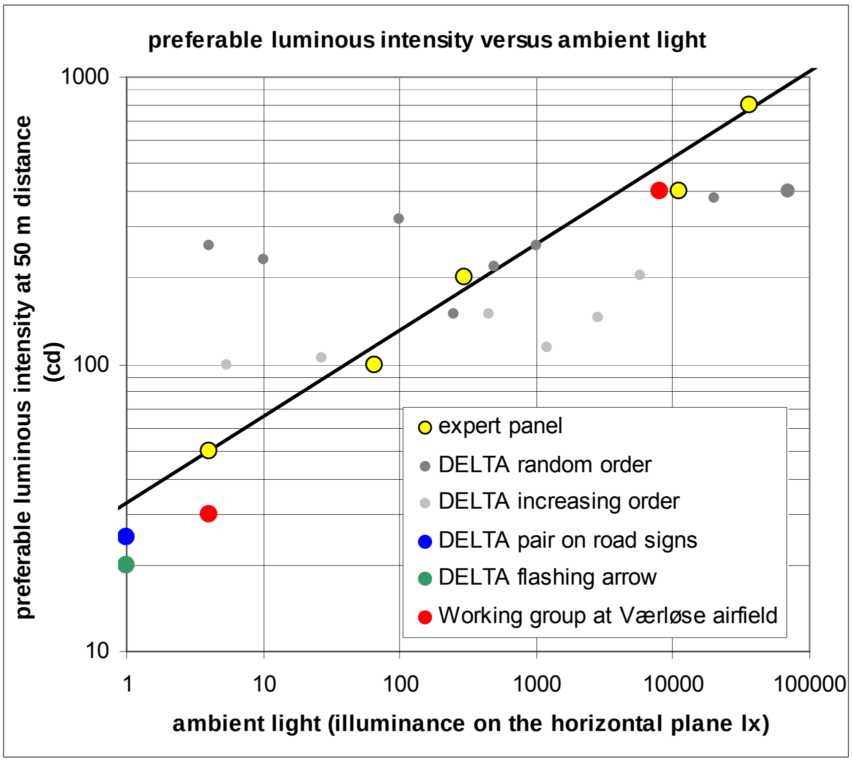

Figure 5.5: Additional evaluations of the preferable luminous intensity.

Figure 5.6: Situation with a yellow flashing arrow.

5.5 Duration of the flash

EN 12352 defines the effective luminous intensity of a flash calculated using the Blondell-Rey equation and defines classes by means of the effective intensity.

Blondell-Rey's equation is:

$$I_{eff} = \frac{\int_{t1}^{t2} I(t)dt}{0{,}2 + (t2 - t1)}$$

where I_{eff}

I(t) is the instantaneous luminous intensity at a point in time t

t1 is the first point in time where $I(t) = I_{eff}$

and t2 is the last point in time where $I(t) = I_{eff}$.

The experimental flashing lights have a constant luminous intensity I_0 within a duration Δt. For such flashing lights Blondell-Rey's equation can be expressed as:

$$I_{eff} = \frac{I_0 \times \Delta t}{0{,}2 + \Delta t}$$

This equation predicts that the effective intensity I_{eff} is reduced as compared the actual intensity I_0.

For flashes of short duration the reduction is approximately given as the proportion between the duration of the flash Δt and 0.2 second. This as if the eye cannot react faster than 0,2 second and that short flashes are averaged over this period of time. The duration of a Xenon flash is measured in microseconds so that the reduction of the effective intensity is very large.

For long durations of light (comparable to 0.2 second) the effective intensity remains significantly smaller than to actual intensity. At a common duration for LED flashes of 0.2 second, the effective intensity I_{eff} is reduced to 50% of the actual intensity I_0.

In order to test if the Blondell-Rey's equation provides a suitable description of the sensation of light, five yellow flashing lights were arranged as shown in figure 5.7 and set to provide intensities and durations as also indicated in figure 5.7. With these settings, the effective luminous intensity is 71 cd in all cases. The period was 1 second. The evaluation was done by the expert panel.

All five flashing lights were judged to appear roughly equal in intensity. This confirms that the Blondell-Rey equation is applicable.

The evaluations for a pair of yellow flashing lights on road signs that are mentioned in 5.4.2 were carried out with flash durations of both 0.2 and 0.5 second. These evaluations provide some confirmation that the effective luminous intensity is the correct measure, refer to ”Preferable luminous intensity of a pair of yellow flashing lights on road signs” by Kai Sørensen and Torben Holm Pedersen, DELTA, 16 January 2008.

However, the following additional observations show that the matter is not always simple.

The lights with the shortest flashes (0.043; 0.02 and 0.009 second) intrude more than the other flashes when they are observed in the peripheral field of view. However, these lights are also difficult to locate in space – the flashes are visible, but there is little impression of location and distance.

This is a disadvantage, and to see if this disadvantage can be eliminated by adding a low level steady background signal, all five lights were given a background signal of approximately 3.5 cd.

The light with the 0.5 second flash duration, having equal on and off periods, seemed odd by shifting between two levels without giving the impression of flashing. The light with the 0.111 second flash duration, on the other hand, still gave the impression of being flashing, and the background signal improved the perception of location and distance. The lights with the shortest flashes (0.043; 0.02 and 0.009 second) gave a clearly more weak impression than the other lights.

The last-mentioned evaluation cannot be explained by Blondell-Rey's equation, which may not be applicable for short flashes on a steady background.

Blondell-Rey's equation was in fact developed to account for single flashes with long intermediate off periods and can probably not be applied in more complex cases such as multiple flashes (for instance three flashes in quick succession).

It is possible that the equation underestimates the effective intensity of flashes with a long duration, but this cannot be decided in the above-mentioned simple evaluations.

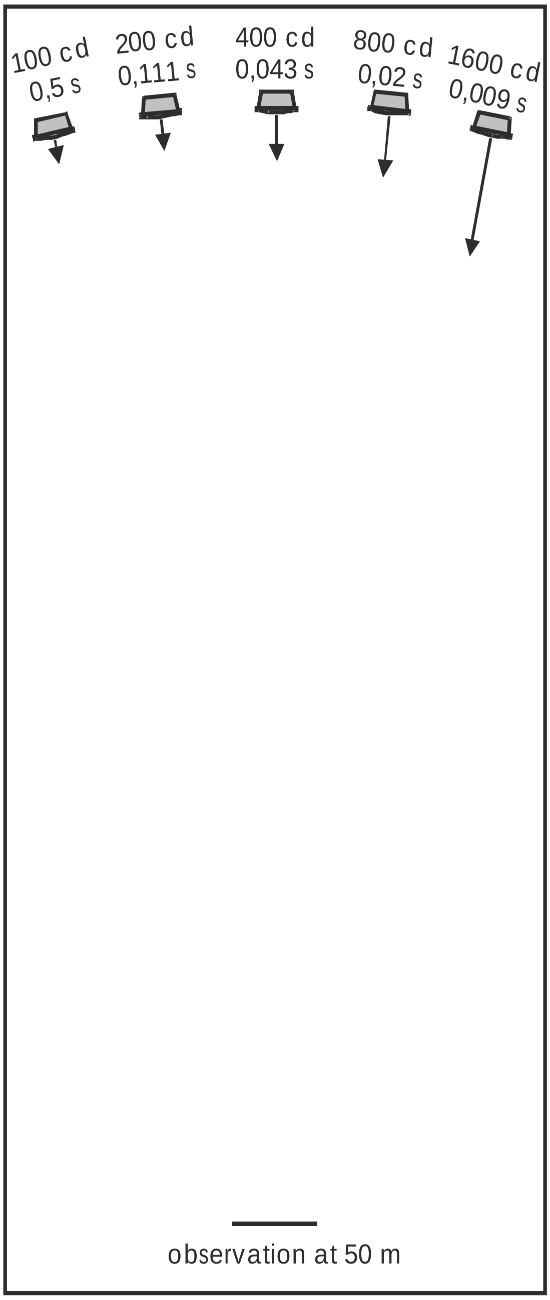

Figure 5.7: Set-up used for the evaluation of the Blondell-Rey’s equation.

5.6 Use of two or more flashing lights

5.4.2 mentions some additional evaluations for a pair of yellow flashing lights on road signs, a number of yellow flashing lights forming an arrow and yellow flashing lights used as sequential running lights.

These evaluations are assumed to confirm the results by the expert panel concerning the influence of ambient light, but also to indicate that the simultaneous use of two or more yellow flashing lights leads to a slight reduction of the preferred luminous intensity as compared to the use of a single flashing light.

The two yellow flashing lights forming a pair on road signs were set to flash simultaneously. This provides a regular impression as opposed to the more disturbing impression giving by alternating flashing. It is not known which is preferable.

The evaluations of yellow flashing lights used as sequential running lights included durations and sequences of the flashes. The conclusions of these evaluations were:

- a very short flash duration – as with xenon flash lamps – makes it difficult to perceive the direction of the sequence, unless the lights have a steady background level
- a flash duration of 0.2 second is preferable to 0.111 second
- an flash duration of 0.5 second combined with a delay time of 0.2 second from one light to the next is confusing because more than one light is on at a time
- the method of individual on-times (turning lamps on one after the other, and leaving them on until the last lamp is being turned off) received good marks.

The delay-time between lights in the sequence was set to 0.2 second in all cases. Such a delay time is found in commercially available sequential running lights and seems to be suitable.

5.7 Conclusions and recommendations

5.7.1 Influence of distance

According to 5.3, the luminous intensity of a flashing light should be in proportion to the square of the distance at which the flashing light is to act. This distance, on the other hand, is related to the driving speed at the location, where the flashing light is to be used.

The relevant distances might be covered by a range from 50 m to 200 m. The shorter distance might be relevant for a city road with a driving speed of 50 km/h and the longer distance for a motorway with a high driving speed. Local speed reductions at road works must be taken into consideration.

It is a traditional concept that a flashing light should be aimed against the traffic in a direction up the road so that a driver at long distances is in the centre of the beam, where the luminous intensity is at its maximum. When the driver approaches, he gets not only closer but also to an increasing angle to the beam, so that the attention effect is roughly constant.

A closer evaluation shows that flashing lights for use at long distance must have powerful, but narrow beam. A flashing light for use at shorter distances can have a weaker, but also broader beam.

In summary, flashing lights with high luminous intensities have narrow beams and are to be used on locations with high driving speeds, while flashings lights with lower intensities have broader beams and are to be used on locations with lower driving speeds. The connection between intensity and beam width is to some degree reflected by the classes defined in EN 12352, and also by the practical use of yellow flashing lights.

5.7.2 Ambient light

According to 5.4 the need for luminous intensity depends on the ambient light measured by the illuminance on the horizontal pane.

The dependence is not strong, a factor of 2 in luminous intensity for each factor of 10 in ambient light. Nevertheless, because of the large scale of ambient light from less than 1 lx in dark surroundings at night to 70,000 lx in sunlight, perhaps by 5 times a factor of 10, it is necessary to regulate the luminous intensity with regard to ambient light.

According to 5.4 the preferable luminous intensity is 25 cd at an illuminance of 0.4 lx and an observation distance of 50 m. According to 5.3 the preferable luminous intensity increases with distance in proportion to the square of the distance.

Table 5.1 shows the combined effect of these relationships.

Table 5.1: Preferable luminous intensities of flashing lights.

Ambient light measured by the illuminance on the horizontal plane (lx)		action distance of the flashing light				
		50 m	71 m	100 m	141 m	200 m
		preferable luminous intensity (cd)				
0,4 lx	(darkness)	25	50	100	200	400
4 lx	(weak road lighting)	50	100	200	400	800
40 lx	(strong road lighting/dusk)	100	200	400	800	1600
400 lx	(twilight)	200	400	800	1600	3200
4000 lx	(weak daylight)	400	800	1600	3200	6400
40 000 lx	(sunshine)	800	1600	3200	6400	12800

The values of table 5.1 can be the basis for setting minimum and maximum requirements for the luminous intensity of flashing lights. In doing this, there are a number of considerations:

a. Observers are fairly tolerant to changes in the luminous intensity. In fact, the luminous intensity can change by a factor of 3 before observers change the average mark by 1, for instance from 2 (a bit too weak) to 3 (preferable).

b. Less powerful flashing lights cause less disturbances to driver by glare or by reflections in wet road surfaces.

c. Yellow flashing lights should match other light sources in the road environment such as vehicle signal lights and headlamps (of the order of 10 to 200 cd).

d. The span between minimum and maximum requirements should be sufficient to allow for normal production tolerances and other variations.

e. Traditional flashing lights in use have in some cases significantly lower luminous intensities – at least in daylight – than those of table 5.1.

Minimum and maximum requirements can be expressed in tables like the table 5.1. The minimum requirements can be lower than the values of table 5.1, but probably not much lower in the case of the first row for 0.4 lx (darkness). The maximum values can be similar to those of table 5.1 or higher.

Tables like that introduce a need for regulation of the luminous intensity with respect to the ambient light.

Regulation is traditionally in two levels, a normal level for daytime and a night reduction level, often with a relatively small reduction factor of for instance 2.

However, the traditional two level regulation cannot meet minimum and maximum requirements defined on the basis of the above-mentioned considerations. It is necessary to introduce additional levels – perhaps even regulation in many steps as known from variable message traffic signs.

Consultations with suppliers of flashing lights indicate that flashing lights based on LED's (light emitting diodes) will gradually replace other types of flashing lights, and that LED based flashing lights can be regulated in several steps.

Therefore, it seems reasonable to introduce requirements for multiple level regulation of flashing lights.

It is pointed out that EN 12352 defines classes combining luminous intensity, beam width and other matters that do not in all cases correspond to requirements as outlined above. EN 12352 also defines classes that support the traditional night reduction.

However, a proposal for requirements should be based on driver's needs. In addition, when possible, it can be pointed out which classes of EN 12352 correspond approximately to individual requirements.

5.7.3 Effective intensity

According to 3.5, the effective luminous intensity according to EN 12352, by means of the Blondell-Rey's, may be a reasonable measure of the impression of light. Therefore, requirements for luminous intensities as discussed in 3.7.2 are to be understood as requirements for effective luminous intensities.

NOTE: The evaluations behind table 5.1 are based either on effective luminous intensities or on a flash duration of 0.5 second, which makes the difference between actual and effective luminous intensities small.

5.5 points to difficulties with short flashes – that they are difficult to locate in space and that the addition of a low level steady background signal causes them to appear less strong. These difficulties can be avoided by requesting that flash durations are minimum 0,1 second.

EN 12352 defines some classes for the flash duration. A class O2 requires that the duration is minimum 10% of the period, which is roughly comparable to a requirement of minimum 0.1 second. This in particular is valid if a class F2, which requires a flash rate of 55 to 65 per minute, is requested. This will in practice eliminate Xenon flash lamps.

5.7.4 Use of two or more flashing lights

The evaluations that are discussed in 3.4 indicate that the differences between preferable luminous intensities of flashing lights for different applications are small. These applications include prewarning flash lights, attention flashing lights on road signs and cross booms, sequential running lights, and flashing arrows and crosses on work vehicles.

Therefore, requirements for luminous intensities as discussed in 5.7.2 can be common for all applications with no need to distinguish between these.

It should be decided if flashing lights forming a pair on road signs or cross boom shall flash simultaneously or alternating.

Finally, the best sequences to be used for running lights should be defined. The evaluations carried out at Værløse airport can serve as a basis, refer to ”Evaluations of sequential running lights at Værløse airport” by Kai Sørensen, DELTA and Britta Fismen, SINTEF, 3 April 2006.

5.8 Literature

EN 12352 ”Traffic control equipment - Warning and safety light devices”

”Preferable luminous intensity of a pair of yellow flashing lights on road signs” by Kai Sørensen and Torben Holm Pedersen, DELTA, 16 January 2008.

”Preferable luminous intensity of a yellow flashing arrow” by Kai Sørensen and Torben Holm Pedersen, DELTA, 28 March 2008.

”Evaluations of sequential running lights at Værløse airport” by Kai Sørensen, DELTA and Britta Fismen, SINTEF, 3 April 2006.

”Forslag til regler for gule blinklygter” (in Danish) by Kai Sørensen, DELTA, 7 April 2008.

6 Work zone illumination

6.1 The importance of lighting

Proper worksite lighting is extremely important with regard to working and safety. The correct implementation of lighting in conjunction with a road that is in use is also very important. The lighting must be in balance with and support traffic guidance. Worksite lighting may not unnecessarily disturb vehicle traffic or cause, for example, dangerous situations due to glare.

The aims of this work did not include an examination of the requirements to be set for the electricity network in worksite conditions. The lighting supply and other worksite electrification must meet the requirements set by the safety standards valid at the time the worksite is in use.

The examinations only studied the light technology and its impact and did not take a position on the mechanical and technical properties of the luminaires. Due to difficult conditions and changing operating situations, the luminaires must be mechanically and technically reliable.

A detour for which the lighting would be separately assessed has not been implemented in the trial arrangements (Pilots) and measurement targets. Detour lighting must be implemented if the road section itself is lit. In such cases, there is reason to critically examine the impact of normal road lighting on so-called optical guidance in order to avoid situations where, for example, a continuous line of luminaires optically guides vehicles directly to the worksite.

6.1.1 Occupational safety

Construction worksites are the riskiest places for occupational accidents. The most occupational accidents per one thousand wage-earners occur in construction.

The majority of occupational accidents at construction worksites take place when moving around the worksite in a constantly changing environment. One reason for this is poorly organised lighting. On the other hand, construction quality has been the target of strong criticism at times. For these reasons lighting should receive the attention it deserves. *(Finnish Institute of Occupational Health)*

The number of occupational accidents in construction work (not only road work) in the early 2000s has been 93-80 per one thousand employees. The occupational accident figure includes serious accidents resulting in at least four days of sick leave. *(Statistics: Finnish Institute of Occupational Health / working conditions in Finland)*

When divided according to accident type (1993), the most common type of occupational accident involved impact with or against an object and falling, slipping or stumbling:

31% impact with or against objects

23% falling, slipping or stumbling

The most prevalent causes of accidents were the work environment and structures as well as articles and objects:

35% were caused by the work environment and structures

27% were caused by articles and objects

(Occupational accident and occupational disease statistics 1993)

Finland does not have a separate register for occupational accidents that occur in conjunction with road worksites. By nature, the work tasks and worksites are similar to those in building construction.

Good lighting meets the following basic needs:

- Visual comfort that provides employees with a sense of well-being and has an indirect effect on high productivity
- Visual performance, allowing employees to complete visual tasks in demanding conditions and for longer periods of time
- Safety.

6.1.2 Work productivity

Various studies have shown that lighting has clear impacts on work productivity. The mechanisms affecting work productivity are visual performance, visual comfort, visual ambiance, interpersonal relationships, biological clock, stimulation, job satisfaction, solving problems, the halo effect, and change process. Not all of the above-mentioned mechanisms are equally important in terms of productivity.

Lighting should be used to influence visual performance and comfort and the visual ambiance at outdoor and road worksites. However, despite various protective measures, people working at outdoor worksites are at the mercy of the weather. For this reason, proper attention to those factors that can be influenced increases motivation or, at least, does not reduce it.

6.2 Worksites

Figure 6.2: Bridge worksite.

The aim has been to extend the inspection to fundamental, typical and long-term tasks that also require the installation of worksite-specific lighting. The inspection and trial arrangements (Pilots) for the study have focused on work types in which the traffic guidance is relatively extensive and important due to work safety and to ensure smooth traffic flow.

6.2.1 Bridge and underpass worksites

Various bridge and underpass worksites are long-term construction projects. These projects involve work tasks that are classified as so-called traditional earth moving work, especially with regard to new construction. In many ways, they are also familiar work phases from property buildings. Bridge repair worksites are projects in which nearly all work phases are performed ’in traffic’. Separate, temporary worksite lighting is arranged for these projects as well as local, job-specific, portable area lighting in many cases.

6.2.2 Tunnels

Work in tunnels always takes place in artificial lighting. The demand levels of the work in the various construction phases of a road tunnel are always different, and thus the phases are also different with regard to vision. The lighting for the actual underground excavation phase of the tunnel does not need to take into account the disturbance caused to other traffic nor does it directly affect perception of traffic guidance.

The tasks performed in tunnels range from excavation to the installation of automatic control and monitoring systems, which requires particular accuracy. Tunnels and their technology also require regular maintenance and cleaning work. Such tunnels already have lighting that simultaneously serves as part of the worksite lighting. The lighting itself also requires regular maintenance/cleaning. In order to be able to utilize the existing tunnel lighting to perform this work, the electric current to the luminaires must be cut off for the duration of maintenance. This report does not examine tunnel maintenance tasks separately.

6.2.3 Work area

When designing and implementing lighting, the work area is that part of the working area where the visual task is performed. In workplaces where the size or location of the work area is unknown, the work area is designated as the area where the work task can be performed.

The table below presents typical worksites and work tasks performed in a traffic environment. The lighting conditions describe how and with which methods the worksite lighting is implemented.

Table 6.1: Lighting conditions at different worksites.

Worksite/	Work/task		Lighting conditions			
	Worksite duration5)	Work task description	Road1)	Worksite2)	Machines3)	Target4)
Underpass Bridge	Long-term	Construction work	1/0	1	1/0	1
	Short-term	Construction work	1/0	0	1/0	1
Earthwork	Long-term	Earthwork	1/0	0	1	–
	Short-term	Earthwork	1/0	0	1	–
Paving	Mobile	Surfacing	1	0	1	–
Tunnel	Long-term	Excavation	–	1/0	1	–
	Long-term	Surfacing	–	1	1	1
	Long-term	Technical installation work	1/0	1	1	1
	Short-term	Maintenance tasks	1/0	0	1	1

1) Fixed road lighting is part of the worksite lighting.

2) Separate fixed general/area lighting is implemented at the worksite.

3) Working lights on excavation and other machines are utilised.

4) In accordance with the nature of the work target and task, additional illuminance is needed, and this is implemented in the form of portable area lighting if necessary.

5) Worksite duration is classified as short-term if the planned duration is less than two working weeks and the work is performed as so-called normal daytime work. If the plan calls for work to be performed at night, for example, lighting conditions at the worksite will be designed to meet the requirements.

The 1/0 – symbols presented in the table describe lighting implementation as follows:

1 => lighting method used as applicable, for example, if the site has functional street lighting.

0 => the lighting method is not actually in use.

– => the lighting method is not appropriate or applicable to the work task concerned.

Paving is mobile work, in which case the lights installed on the machines serve as worksite lighting and fixed road lighting are also part of worksite lighting on lit road sections.

6.3 Lighting requirements and tasks

6.3.1 Lighting requirements (EN 12464-2)

The qualitative and quantitative lighting requirements for outdoor areas are presented in standard EN 12464-2 (The following table presents the recommended illuminance levels in work places in accordance with EN 12464-2. The table values that best correspond to the description presented in the **purpose** field of the table with regard to the conditions or the work and related visual task should be applied.

Increasing or decreasing the maintained lighting level

Lighting level higher than the standard

According to the work lighting standard for outdoor work places, the maintained lighting level must be raised if:

- Visual tasks are critical to the work
- It is expensive to correct errors
- Accuracy or higher productivity are very important
- The employee’s vision is poorer than normal
- The details of the objects being viewed are small or contrast is low
- Work is done for an exceptionally long period of time.

The lighting level must be increased if so required by one or more of the above conditions or factors related to vision and work. The average illuminance values presented in the standard shall be increased by at least one value according to the following classification: 20->30->50->75->100->150->200-> 300. For example, if the required limit value is 50 lux, the value shall be raised to 75 lux.

Selection of illuminance

The following table presents the recommended illuminance levels in work places in accordance with EN 12464-2. The table values that best correspond to the description presented in the **purpose** field of the table with regard to the conditions or the work and related visual task should be applied.

Table 6.2: Recommended illuminance (EN 12464-2).

Purpose of the area	E_m	U_o	GR_L	R_a	Note
Areas of general movement					
Traffic areas where driving speed < 10 km/h	10	0,40	50	20	
Traffic areas where driving speed < 40 km/h	20	0,40	45	20	
Pedestrian crossing and turning, loading and unloading sites	50	0,40	50	20	
Construction and other worksite areas					
General lighting in a construction worksite yard	50	0,40	50	20	
Excavation, clearing and loading work	20	0,25	55	20	
Installation of rainwater pipes, storage areas, transport routes	50	0,40	50	20	
Installation of frame elements and electrical pipes, cabling and wood frame erection	100	0,40	45	40	
Connection of elements, demanding electrical work, machine and pipe installations	200	0,50	45	40	

E_m = Average minimum illuminance (lux)

U_o = Minimum uniform luminance

GR_L = Maximum allowable glare

R_a = Minimum colour rendering index value

The illuminance values are so-called maintenance values that must be met, even in ageing installations. Maintenance of lighting and the related cleaning ensures that the luminaires produce the planned light power.

6.3.2 Tasks of lighting

Essential to good lighting – in addition to the required illuminance – is the satisfaction of quality requirements such as uniformity, reflection glare and colour rendering.

Measurements and calculations showed that the illuminance levels presented in the standard are easily exceeded at, for example, a normal size bridge worksite. It is not practical to minimize the illuminance levels, because these types of worksites are short-term with regard to energy consumption and the associated need for savings.

Furthermore, in practice luminaires are often rented for worksites, meaning that the equipment and its efficiency determine the level of lighting to a certain degree.

Based on the standard, the lighting levels at road worksites are determined using the so-called elevated limits because errors are often expensive to correct, accuracy and productivity are important, employees' vision or the visibility conditions may be worse than usual as a result of, for example, weather conditions.

A further challenge to lighting conditions at worksites is the fact that employees change more often than earlier because the work is now distributed to more groups/subcontractors. Work is divided into different phases and assigned to experts in that sector. It must be easy for employees that are not at the worksite continuously but only come for certain periods to perform their specific phase to detect new risks caused by a regularly changing situation. Worksite schedules and work productivity expectations require optimal working conditions in view of the conditions.

6.3.3 The worksite area and its immediate environment

In compliance with the recommendations of the standard, the illuminance levels in the working area (the area where the actual visual task is performed) at the work site and its immediate environment are presented in the following table.

Table 6.3: Illuminance recommendations for the working area and its immediate environment.

Illuminance in the working area (lux)	Illuminance in the environment of the working area (lux)
200	50
150	30
50< E <100	20

When the illuminance of the target is 30 lux or less, the same illuminance is used throughout the area.

The illuminance in the immediate environment must be relative to the illuminance in the working area and must achieve a balanced luminance distribution in the vision field. In practice, lighting in the immediate environment of road worksites is the same as the general lighting in the worksite area.

6.3.4 Mobile worksite

The following diagram presents a specification of the area of a mobile worksite to be lit.

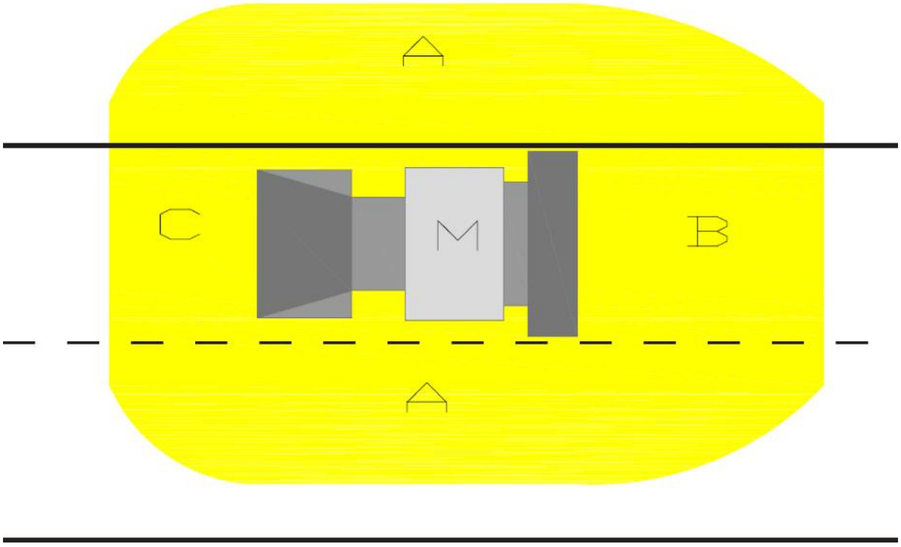

Figure 6.3: Area of a mobile worksite to be lit.

M = Mobile machine, for example, an asphalt spreader

A = Working area on the side of the machine where work is performed on foot.

The lit area must extend 3 metres from the side of the machine.

At least the traffic side of the machine must be lit.

B = Working area behind the machine where work is performed on foot.
The area must extend for 5 metres.

C = Working area in front of the machine where work is performed on foot.

The area must extend for 5 metres.

The illuminance in the defined area must be Em = 30 lux and uniformity $U_o = 0.4$.

The working lights installed on the edge of the machine roof help to achieve the required illuminance. Care must be taken when aiming the working luminaires in order to avoid them causing glare to passing traffic. If necessary, protection from the glare of the luminaires must be improved using a separate grate or peak.

6.4 Lighting design

The worksite functions, work tasks and their level of demand serve as the foundation for the dimensioning of lighting. The size of the worksite and the placement of its functions as well as the most important routes also set requirements for implementation of lighting.

Figure 6.4: Example of work task that needs a specific worksite lighting plan.

6.4.1 Worksite lighting plan

The customer determines the extent of the worksite, which the contractor then supplements with its own worksite plan as work progresses. Proper lighting levels are planned and implemented by work point in accordance with the demands of the tasks. When planning general lighting, it should be ensured that the lighting levels in the immediate environment are sufficient to achieve a balanced luminance distribution. Changes in, for example, routes caused by the progress of the worksite should already be taken into consideration in the planning phase.

Content of the worksite lighting plan:

- Description of the target level of lighting in different parts of the workplace in accordance with progress and work phases of the workplace.
- The types, numbers and location of luminaires and lamps.
- The types and number of local/area luminaires.
- Future, permanent lighting that may already be taken into use during the construction phase.
- Utilisation/importance of the use of existing, for example, road lighting as worksite lighting.
- The effect that glare caused by worksite lighting has on traffic and measures needed to prevent that effect.
- Electricity network for lighting.

6.4.2 Lighting levels

The illuminance levels that correspond to the tasks at the site are selected from the table in the EN 12464-2 standard. The values in the standard can all be measured and calculated and are thus verifiable.

A preliminary calculation of the amount of light needed in the area can be calculated using the so-called efficiency method:

$$\Phi = \frac{E * A}{\eta_L * \eta_V}$$

Φ = required lumen flux produced by all the lamps (lm)

E = the target illuminance in the area (lx)

A = area of the space (m^2)

η_L = efficiency of the luminaire

η_V = efficiency of the lighting

6.4.3 Shadow formation

Correct shadow formation is a very important factor in terms of understanding a three-dimensional shape and perception of entities. Shadow formation and perception of a shape is achieved by producing light on the target from at least two directions. The light has a so-called main direction while light from another direction is used to soften the shadows. If necessary, local lighting in the direction of the surface is used to achieve strong shadow formation, for example, in order to examine the uniformity and quality of a surface.

The light should be as vibration free as possible in order to avoid causing additional strain on employees.

When road lighting is part of worksite lighting, it is important to ensure that, as a continuous thread, it does not serve as misleading optical guidance, for example, in the use of a detour. This factor should always be examined for all lighting equipment at the worksite.

6.4.4 Limiting glare

Limiting glare is important in order to avoid errors, tiredness and accidents. It is particularly important when the gaze is directed upwards from the horizontal.

Discomfort glare at work places is usually caused by bright luminaires. If discomfort glare can be eliminated, glare reduction is not usually a problem. For example, bright light sources cause glare and decrease visibility of the targets. Glare can be limited by means of suitable glare protection on luminaires and luminaire placement.

6.4.5 Luminaires

Observations and measurements made in conjunction with the Pilots show that glare caused by worksite lighting on a road that is in use is a major disturbance and thus also a risk factor.

The lighting levels at worksites are relatively low, and quite large areas need to be lit. The luminaires are installed at a relatively low height, because portable and easily erected masts are often used. The luminaires suitable for this purpose are floodlights with a so-called wide or medium-wide light distribution.

In asymmetrical floodlights the peak direction angle of luminosity can be 45°–65° upwards from the perpendicular of the shutting glass. If the direction angle is 65°, the floodlight does not need to be and should not be tilted more than 0°–10°. Thus, disturbing light and glare in the environment remain at a low level while uniform lighting is maintained. The wind load for a floodlight that is directed nearly downwards also remains quite small, thus making lighter mast structures possible.

In many cases, the surface of the actual work target is vertical. This should be taken into consideration when aiming lighting so that the light is also projected towards those parts that are above a 45° angle. It is often quite easy to produce sufficient lighting for the work in question with asymmetrical floodlights in which the direction angle of the light peak is greater than this angle. If floodlights with symmetrical light distribution are used in a manner that prevents glare, the angles of direction remain small, in which case the vertical surfaces do not receive enough light.

6.4.6 Masts

The installation height of luminaires is determined on the basis of the worksite and the area to be lit. The height of the masts or other equipment on which the luminaires are installed must be in h/d relationship to the area being lit.

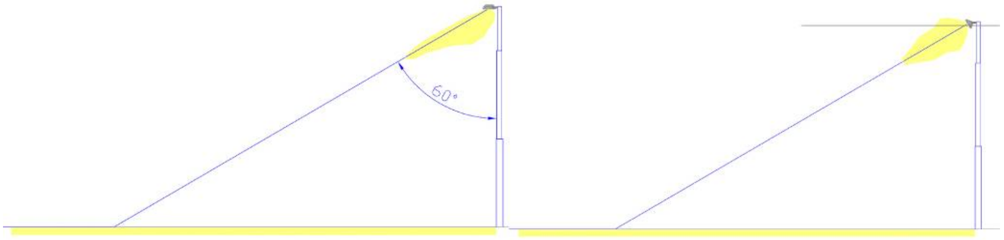

Figure 6.6: The difference between asymmetrical and symmetrical light distribution in area lighting.

The above diagrams show the difference between floodlights with asymmetrical and symmetrical light distribution in area lighting when the mast height is low. The coloured area at the bottom represents the area to be lit as 2 x mast height (d=2xh).

6.4.7 Lamps

Table 6.4: Comparison of the most common light sources.

Lamp type	Power (W)	Recommended*) installation (m)	Light output 1,000 (lm)	Colour temperature (K)	Colour rendering (Ra)	Effective life (h)	Light production when switched on
Halogen	500	3–5	10	3000	100	2,000	Immediate
	1000	5–10	24				
High Pressure sodium	100	3–5	10,2	2000–2500	20–60	16,000	1–2 min**)
	150	5–10	17		20–60		
	250	10–12	33		20–60		1–2 min***)
	400	12–18	55		20–60		after being switched on again
Metal halide	70	3–5	6,6	3000–4500	>80	12,000	3–5 min**)
	150	5–10	13,5		>80		
	250	10–12	25		>80		5–10 min***)
	400	12–18	42,5		>80		after being switched on again

*) Recommended installation height in the general lighting of the area.

**) The light output produced by the lamp is > 90% of the value after reaching the operating temperature.

***) Time required for the lamp to re-ignite after even a short interruption in voltage or a quick change in voltage.

When using high pressure sodium or metal halide lamps, it must be noted that even a small interruption in voltage or quick drop in network voltage, for example, due to a high load, will extinguish the lamp. Re-ignition of the lamp can take minutes.

The light efficiency lm/W of such a lamp is many times greater than that of halogen lamps. For example, the light production of a 100W high pressure sodium lamp is equivalent to that of a 500W halogen lamp.

LED lighting is developing rapidly. At this time, their light and unit efficiencies are still so low that they are not an economic lighting solution for area lighting at worksites. Due to good vibration tolerance they could soon be used in small, portable area lights.

6.5 Implementation, use and maintenance of lighting

6.5.1 Implementation and use

A review is performed in conjunction with the start-up of the worksite to examine how well the lighting complies with the plans and targets set for it. The review/inspection shall also be carefully conducted with regard to passing traffic. The Pilot trial arrangements and assessments performed in conjunction with them show that a visual inspection is also necessary to examine how the lighting and traffic guidance work together.

The direction and rotation angles specified in the lighting plan shall be observed when aiming the floodlights. When positioning an asymmetrical floodlight, the light output direction angle must be obtained from the designer or the luminaire supplier.

6.5.2 Maintenance

Worksites are constantly changing. Structures that have previously prevented glare may be removed from directions that cause glare. The condition of the lighting shall also be checked in conjunction with the weekly worksite maintenance inspection. **During the inspection, the appropriateness of the lighting in relation to the current situation at the worksite shall be examined**.

During inspection of the positioning of the luminaires, it must also be ensured that no changes have occurred that could cause glare towards traffic.

The impact on traffic must also be examined whenever changes to lighting are made in accordance with the requirements of the worksite.

- General lighting
- Area lighting

6.6 Pilot trials

Conclusions

Lighting shall be implemented with floodlights that have an asymmetrical light distribution. This will help to avoid causing disturbing light in the environment and also prevent glare without separate grates or limiters.

Possible glare at the worksite caused by traffic was identified at the beginning of the project as an issue that needed clarification. The measurements performed showed that the lights of passing vehicles do not disturb work. The light distribution from cars is very limited and the output relatively small if the lighting level at the worksite complies with the norms.

Poorly implemented worksite lighting causes a dangerous level of glare to passing traffic, thus hindering and even preventing visibility with regard to traffic guidance arrangements.

Construction worksites are always temporary and relatively short-term in nature, meaning that it is not always ‘practical’ to monitor the efficiency of lighting in relation to consumption. It is important to reliably produce light that allows work under changing work conditions.

The installation geometry used in the trial, in which symmetrical luminaires were aimed towards traffic, should be banned because the luminosity from the luminaires projected towards the observers is high. In practice, symmetrical floodlights without glare shields or limiters should only be used if the angle of tilt is less than 30°, in other words, when using relatively high lighting masts. In this case the problem is obtaining sufficient light on vertical surfaces, for example, walls, which are often the actual target of the work.

7 Specular road surface reflections at night

7.1 Specular reflection in general

Figure 7.1 shows a road crossing at night in situations with a dry and a wet road surface. In both situations the headlamps on vehicles provoke specular reflections in the form of bright patches stretching from the headlamps in directions towards the observer. The patches are long and narrow and they are seen to brighter for the wet condition than for the dry condition. In the wet condition, even signal heads and tail lamps on the vehicles contribute with fairly bright reflections.

Specular reflections as illustrated in figure 7.1 make the driver's visual task more difficult by adding to the complexity of the road scenario and by hiding road markings. This applies as well for major road works where light sources such as warning lights and luminaires for work lighting – and even retroreflectors – may cause specular reflections.

It is the purpose of this chapter to provide information on specular reflections and some advice regarding means to reduce their adverse effects.

An account of specular reflection is given in 7.2 including general observations, a physical model for the specular reflection and a test method for field measurement

Some specular reflection values as measured in road in Denmark, Norway and Sweden are introduced in 7.3.

Finally, the possible adverse effects of specular reflections in road works are discussed in 7.4, where some recommendations for how to reduce adverse effects are provided as well.

Figure 7.1: A road crossing at night in the dry condition (top) and a wet condition (bottom).

7.2 Physical account of specular reflection

7.2.1 General observations

Specular reflection is caused by surface reflection in facets of the road surface.

Surface reflection is guided by the Fresnel law as illustrated in figure 7.2 for both a stone surface and a water surface. The stone surface is representative for the dry condition and is assumed to have a refractive index of 1,55 typical of glassy surfaces, while the water surface is representative for wet conditions (where facets are covered by a water film) and has a refractive index of 1,335.

Figure 7.2 shows that the reflectance of surface reflection is high when the entrance angle is close to 90°. This means that strong specular reflection is reserved for geometrical situations where the incoming light is reflected through a small angle. This causes, almost like a geometrical law, that specular reflections appear to be long and narrow.

It is a further consequence that a light source that is close to the road surface, such as a headlamp on a vehicle, causes specular reflections at a short distance in front of it. The illumination is strong because of the short distance and, accordingly, the specular reflection is strong, but also limited in extent.

A light source that is high above the road surface, on the other hand, such as a luminaire for work lighting, causes a specular reflection that is less strong, but of greater extent.

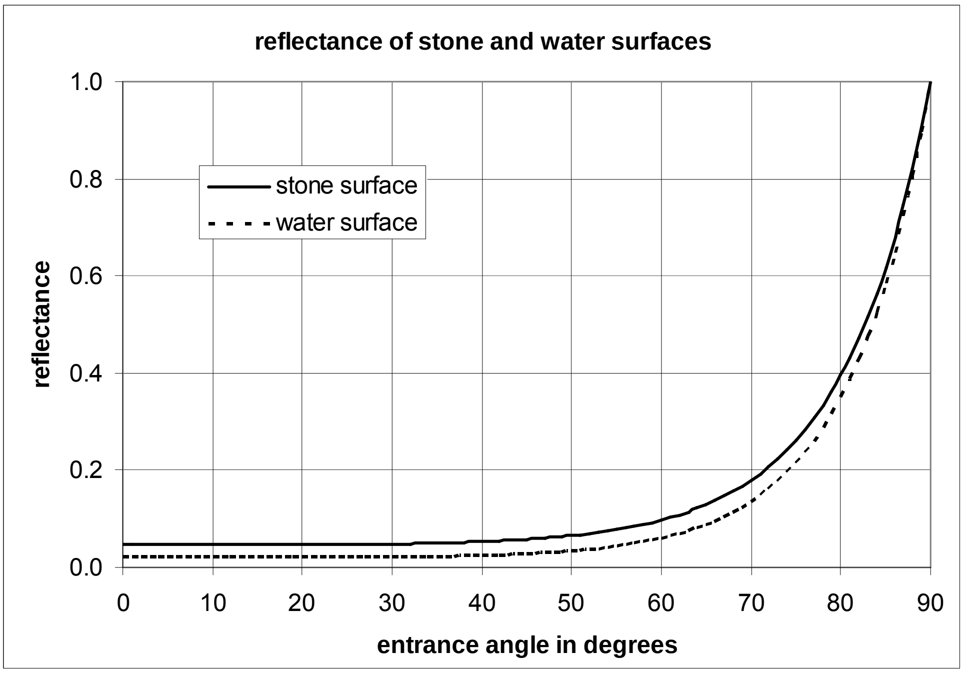

Figure 7.2: Surface reflectance of stone and water surfaces.

Figure 7.2 shows that the surface reflectance is actually higher for a stone surface than for a water surface and, therefore, it needs to be explained why specular reflections are actually stronger for wet than for dry surfaces.

The explanation is that a road surface has both microtexture and macrotexture. Even a round stone in the surface has got some microtexture that causes absorption and scattering of the incoming light. When the surface is wet, the microtexture is covered by a water film so that larger areas are available for reflection.

This is also the reason that the degree of wetness influences the specular reflection. A more wet the surface has a more thick water film, and a more powerful specular reflection. In the extreme case, when a surface is covered by a water surface, it acts like a mirror.

7.2.2 A model for the specular reflection

Light & Optics note No. 2 accounts for detailed measurements of the specular reflection of eight road surface samples in both a dry and a wet condition.

It is surprising that all 16 cases, eight surfaces in two conditions, can be explained by the same assumption regarding facets available for surface reflection. The assumption is that active facets within a road surface area A can form a round surface of a particular shape with a basis area a.

Refer to figure 7.3.

The proportion f = a/A is characteristic for each of the above-mentioned 16 cases while the shape of the round surface is the same; the cross section is the upper half of an ellipse with a height of 0,125 times the diameter of the base.

The reflection values are presented by means of the coefficient of reflected luminance R_L, which is the proportion between the luminance L of a field of the surface and the illuminance E at the field on a plane perpendicular to the direction of illumination. The unit is $cd \cdot m^{-2} \cdot lx^{-1}$. According to the model, the reflection value is given by:

$R_L = (f \times \rho \times SRF)/(4 \times \sin\alpha)$

where f is the proportion a/A

ρ is the reflectance of surface reflection according to figure 7.2

SRF is a value of a 'Surface Roughness Function'

and α is the angle between the observation direction and the road surface

The surface roughness function SRF is a function of the angle of tilt v of the round surface at the location, where the reflection takes place. This function is shown in figure 7.4 for the round surface of the model.

This model is of course not strictly accurate. Figure 7.5 illustrates the correlation between measured reflection values, and values calculated according to the assumption for one of the samples in the wet condition.

Ideally, all the points should lie on a 45° line. There is significant divergence from this line for the smaller reflection values. However, for the most important higher values, and in view of the large variation of specular reflection to be considered later, the fit is acceptable for practical purposes.

Therefore, the model is used in the following; it predicts that the shape of specular reflections is independent of the road surface, but that the strength of reflection is characteristic of the surface and may be presented by the proportion f, or by a reflection value for a single geometry.

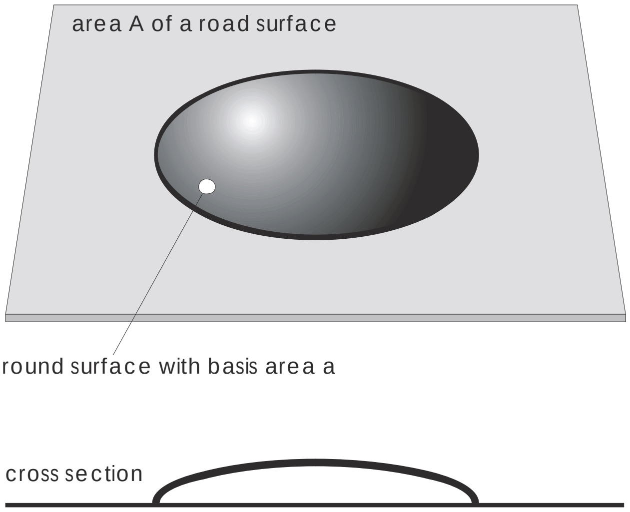

Figure 7.3: Active facets within a road surface area A can forming a round surface of a particular shape with a basis area a.

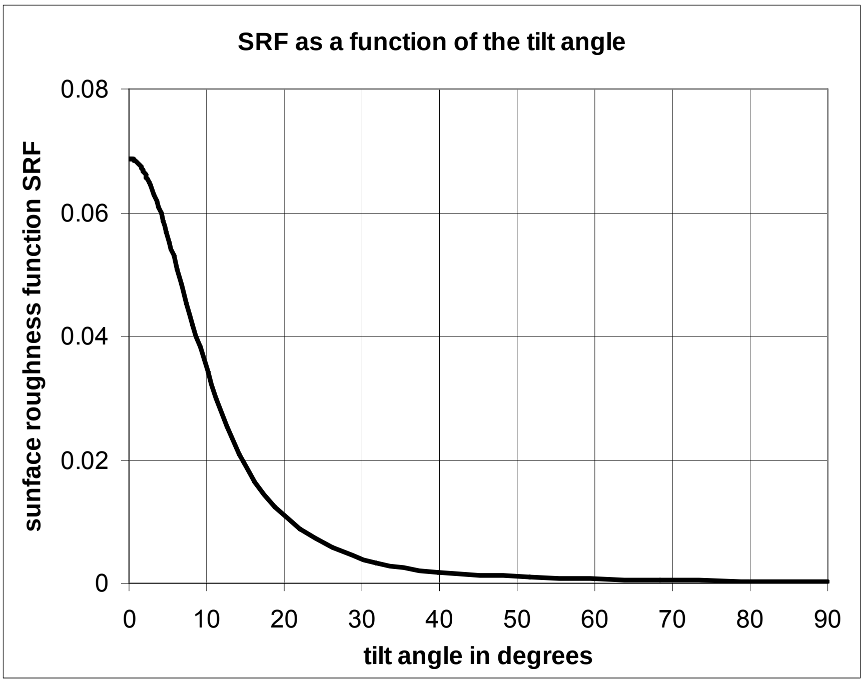

Figure 7.4: The surface roughness function as a function of the tilt angle in degrees.

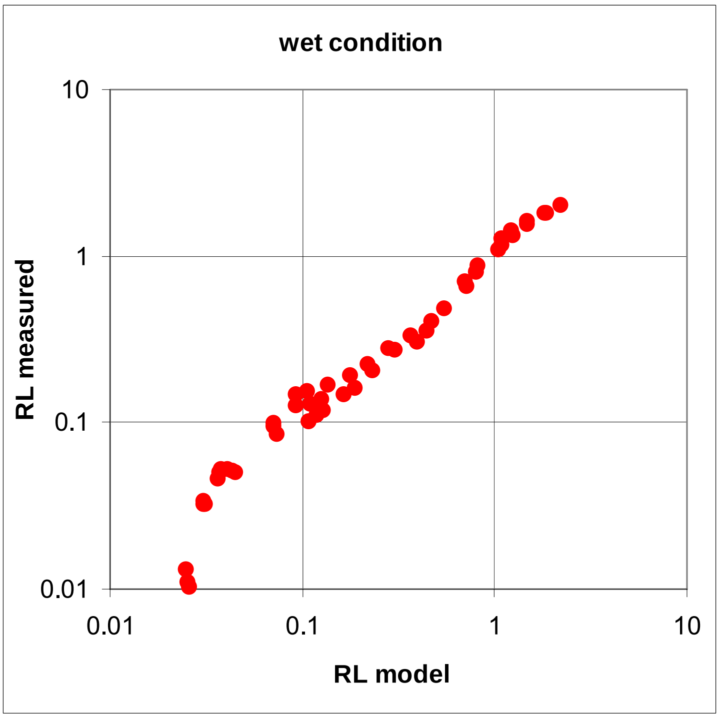

Figure 7.5: Comparison of measured R_L values and model R_L values for a particular case.

7.2.3 Test method for field measurements

It is sensible that the single geometry mentioned in 7.2.2 is obtained from the CEN 30 m geometry defined in EN 1436 by conversion from a retroreflection geometry to a specular reflection geometry. The converted geometry is shown in figure 7.6; it corresponds to a central location within the reflection patch and relatively large reflection values.

With this geometry, handheld retroreflectometers using the CEN 30 m geometry can be modified to provide the specular reflection value instead of the retroreflection value. Such an instrument is shown in figure 7.7. The modification is to add a vertical, mirror surface in front of the surface, so that the observation direction is turned backwards.

A special precaution is to use the front surface of a black acrylic plate as the mirror surface. The front surface has a reflectance of only 4%, so that readings are reduced by a factor of 0,04. This is practical in order to avoid saturation of the readings (specular reflection in wet road surfaces is much stronger than the retroreflection of road markings that the instrument is designed for).

With this particular instrument, the measured field is so large, that the instrument includes simultaneously the retroreflection value in full and the specular reflection value reduced by the above-mentioned factor of 0,04. However, the retroreflection value of wet road surfaces is small, while the specular reflection is so high in spite of the reduction, that it is permissible to ignore the addition of the retroreflection value.

For this geometry, the relationship between the proportion f =a/A defined in 7.2.2 and R_L is:

$R_L = 26{,}5 \times f$ $(cd \cdot m^{-2} \cdot lx^{-1})$ for dry road surfaces

$R_L = 26{,}2 \times f$ $(cd \cdot m^{-2} \cdot lx^{-1})$ for wet road surfaces.

NOTE: The slight difference in the two expressions is due to different assumptions regarding the refractive indices of stone surfaces and water surfaces of respectively 1,55 and 1,335.

According to these expressions, values larger than approximately 26 $cd \cdot m^{-2} \cdot lx^{-1}$ should not occur in practical measurements. But higher values are in fact obtained in measurements, refer to 7.3. This is another indication that the model is an approximation.

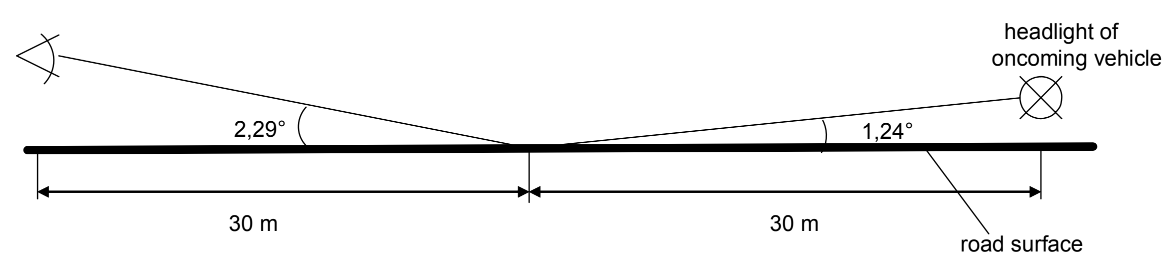

Figure 7.6: A single geometry for specular reflection.

Figure 7.7: A handheld retroreflectometer using the CEN 30 m geometry with modification to provide the specular reflection value instead of the retroreflection value.

7.2.4 Estimates of normally occurring specular reflection values

The design of road lighting installation on traffic roads involves the road surface reflection by means of tables of reflection values. Refer to CIE 144.

The tables used in Denmark and some other countries are labelled N2, N2, N3, N4, W1, W2, W3 and W4 and form a series of increasing degrees of specular reflection. The tables N1, N2, N3 and N4 are meant to represent dry road surfaces, while the tables W1, W2, W3 and W4 are meant to represent wet surfaces.

Some countries use tables labelled R1, R2, R3 and R3 instead of N1, N2, N3 and N4. This does not make much difference as the degrees of specular reflection are much the same.

It is possible to derive approximately the area proportion f of 2.2.2 from these tables and thereby estimate the specular reflection R_L values in the standard geometry of 7.2.3. These are plotted in figure 7.8.

As dry road surfaces are normally represented by tables N2 and N3 (R2 and R3 in some countries) specular reflection R_L values of a fraction of 1 $cd \cdot m^{-2} \cdot lx^{-1}$ should be expected for road surfaces in this condition. Wet road surfaces, on the other hand, are often represented by tables WG3 and WG4 so that R_L values from one to a few $cd \cdot m^{-2} \cdot lx^{-1}$ should be expected.

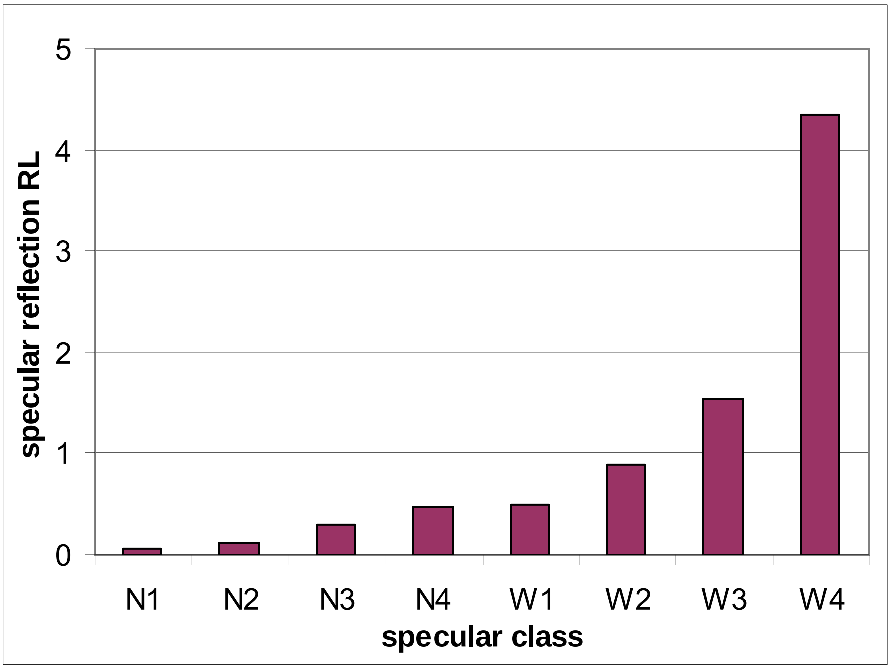

Figure 7.8: Approximate specular reflection R_L values in $cd \cdot m^{-2} \cdot lx^{-1}$ for road reflection tables.

7.3 Measured specular reflection R_L values

7.3.1 Samples of road in Denmark, Norway and Sweden

The roads were selected so as to represent types of road surface normally used on major roads in the Nordic countries.

Measurements of specular reflection values were done using the modified instrument described in 2.2.3. Measurements were done both for the dry condition and for a the wet conditions occurring right after pouring water from a bucket over the measuring location, 15 seconds later and finally 60 seconds later.

The specular reflection values are lower for the dry and for the wet conditions, and decrease quickly with time after adding water.

The wet condition after 60 seconds is thought to be the most interesting as this is the same wet condition that is used for the retroreflection of road markings according to EN 1436. This condition is known to be more wet than those moist and wet conditions that occur in long periods in the Nordic countries and corresponds perhaps to a light rain.

The results for the wet condition after 60 seconds are provided in tables 7.1, 7.2 and 7.3 for roads in respectively Denmark, Norway and Sweden.

Additional measurements were carried out using other instruments. Refer to the report “Spegling i våta beläggningar, Störande ljus vid vägarbeten om natten”, Sara Nygårdhs, 2005 for more details.

The major city roads in Copenhagen, refer to table 7.1, show in some cases values that are very high or even marked by overflow as 100 $cd \cdot m^{-2} \cdot lx^{-1}$ or higher. These values reflect probably the compression and polishing of the road surfaces by very high traffic loads.

In other cases, the measured values are mostly within the expected range from one to a few cd·m^{-2}·lx^{-1}, refer to 7.2.4.

One exception is the road surface in Norway described as ”soft”. This road surface has probably been compressed by traffic loads to become fairly specular.

A few other cases stand out with high specular values. The reason is probably a high variation of the specular reflection with the local road surface conditions. That the variation is large can often be observed visually, refer to figure 7.9.

Studded tyres are used to a much larger extent in Norway and Sweden than in Denmark, and therefore – to resist the heavy wear by studded tyres – the road often have large aggregates. For this reason, and because of the action of the studded tyres themselves, it was expected that the level of specular reflection would be relatively low in Norway and Sweden. This, however, is not verified in the data.

Table 7.1: Specular reflection values R_L (cd/m^2/lx^{-1}) of some major roads in Denmark.

Specular reflection values cd/m^2/lx^{-1}	**Major city roads in Copenhagen**						**Major rural roads**				
	Hareskovvej-Mellemvangen, south	Hareskovvej-Mellemvangen, north	Åboulevarden-H.C. Ørsteds Vej	H.C. Andersens Boulevard-Vester Farimagsgade	Amager Boulevard-Artillerivej,south	Amager Boulevard-Artillerivej, north	Light asphalt concrete, 11 mm	Dark asphalt concrete, 12 mm	Dark asphalt concrete, 8 mm	Light asphalt concrete, 8 mm	Light asphalt concrete, 11 mm
Between wheel tracks	4,5	9,5	36,5	>100	23,0	19	3,2	4,0	4,2	0,8	0,9
In the right wheeltrack	25,2	3,3	<100	>100	>100	3,5	4,3	4,0	3, 1	0,6	1,3

Table 7.2: Specular reflection values R_L (cd/m^2/lx^{-1}) of some major roads in Norway.

Specular reflection values cd/m^2/lx^{-1}	**Road surface (asphalt concretes)**									
	11 mm		11 mm		16 mm		11 mm		11 mm soft	
Location	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Left	1,7	0,86	2,4	64,4			1,6	2,2	6,6	5,4
Left wheeltrack	3,0	1,7	1,0	0,9			1,6	2,5	6,7	6,3
Between wheeltracks	20,5	5,5	0,9	1,0	0,7	1,4	1,2	2,3	7,0	7,3
Right wheeltrack	7,0	2,0	1,1	0,8	0,5	9,4	2,1	1,8	6,9	6,7
Right	1,9	4,0	7,5	8,3	1,3	2,0	1,4	2,8	5,6	8,1

Table 7.3: Specular reflection values R_L (cd/m^2/lx^{-1}) of some major roads in Sweden.

Specular reflection values cd/m^2/lx^{-1}	**Road surface**										
	Asphalt concrete, 16 mm			Surface treatment, 12 mm		Asphalt concrete, 11 mm		Asphalt concrete, 16 mm		Asphalt concrete, 12 mm	
Location	**1**	**2**	**3**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Left	2,0	1,6	1,4	3,0	2,7	1,2	1,0	6,3	2,0	2,1	3,4
Left wheeltrack	20,6	4,1	5,1	2,7	8,0	2,5	1,4	9,1	14,8	1,7	1,5
Between wheeltracks	4,8	7,1	1,8	3,2	2,6	1,2	1,2	1,5	1,2	2,6	2,3
Right wheeltrack	2,3	1,5	75,8	2,6	3,1	1,5	3,3	1,1	1,5	1,9	2,1
Right	0,9	1,5	0,9	1,6	2,3	1,4	1,7	>100	1,7	2,2	2,2

Figure 7.9: Example that a large variation of the specular variation can be observed visually.

7.3.2 Further measurements on roads in Denmark

The previous section shows that most road surfaces have specular reflection values up to a few of cd/m^2/lx^{-1}, while a few road surfaces show much higher values. The question is then if surfaces with high specular reflection values can be identified by simple observation or by means of other road surface characteristics like skid resistance and texture.

There roads were selected among from the road network in the previous county of Frederiksborg so as to show a high variation in types and wear. Measurements were done for the wet condition obtained 60 seconds after adding water at 23 locations, both in the right wheel track and between wheel tracks

Initially, the skid resistance obtained by the SRT tester was used at all measuring locations. However, it turned out that there is no obvious correlation between the SRT values and the specular reflection values and, therefore, the SRT measurements were abandoned and are not considered in the following. Close up photographs of all the road surfaces are available, but seem to be of little help in predicting cases of strong specular reflection.

At a later point in time, measurements of the mean profile depths were done at the locations by the Danish Road Institute using a laser profilometer.

Figure 7.10 shows that there is some correlation between the specular reflection values (provided as averages for the two transverse locations) and the mean profile depth.

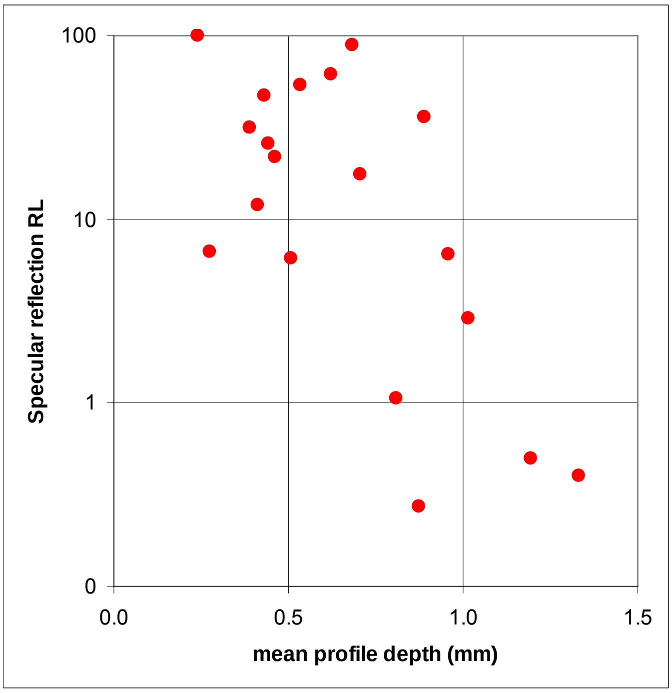

Figure 7.10: Correlation between the mean profile depth (mm) and the specular reflection value R_L ($cd/m^2/lx^{-1}$).

It is obvious that specular reflection should have some correlation with texture, and therefore one might look for a reason why figure 7.10 does not show a strong correlation.

One reason might be that the mean profile depth is not the relevant measure of texture in this connection, as the specular reflection is perhaps more affected by the shape of the texture than by the size. Another reason might be a mismatch between the locations where the two characteristics were measured (the mean profile depths were obtained as averages over a certain length of road at a transverse location that did not match any of the two transverse locations at which the specular reflection values were obtained).

In any case, road surfaces with little texture as reflected by a low mean profile depth may be expected to show a strong specular reflection.

General observations may be helpful. Figure 7.11 shows strong specular reflection of vehicle headlamps and is indeed a surface for which high values were measured. Figure 7.12 shows strong specular reflection of the sky, and is also a surface for which high values were measured.

Figure 7.11: Strong specular reflections of headlamps.

Figure 7.12: Strong specular reflection of the sky.

7.4 Possible adverse effects of specular reflections and recommendations

Headlamps on vehicles are frequent and powerful light sources in the road environment and they sit low. Opposing traffic streams are often directed close to each other at road works so that opposing headlamps become a strong source of glare.

The question in this connection is if headlamps can cause substantial additional glare by specular reflection in the road surface.

According to the reflection model introduced in 7.2.2, the total luminous intensity of the reflection in front of a headlamp with a luminous intensity of 10,000 cd in directions towards the road surface can become no higher than approximately 100 cd. This is to be compared to the direct luminous intensity in directions towards other drivers that is typically 200 cd.

Therefore, it should be concluded that headlamps cannot cause serious glare by reflections in addition to the glare they cause directly. This should apply for other light sources in the road environment as well.

NOTE: The completely flooded road surface is of course a particular case that is not covered by the model. A water surface is able to reflect the full intensity of headlamps and other light sources.

The next question is if headlamps and other light sources can cause reflections with enough luminance to disturb the visibility of road markings. To answer this question, is sufficient to compare R_L values of road markings in retroreflection to R_L values of road surfaces in specular reflection.

For the dry situation, these R_L values typically match each other being of the order of 0.1 $cd \cdot m^{-2} \cdot lx^{-1}$ give and take. For wet conditions, on the other hand, the R_L values of road markings are mostly a small fraction of a unit, while the R_L values of road surfaces are easily a full unit or several units.

This shows that, at least for wet conditions, specular reflections of opposing headlamps can easily make it difficult to see road markings. Other light sources in the environment may well be able to do the same. This, on the other hand, may not impair the drivers in finding their way through road works as other means of direction and guidance are mostly available.

The third question is if specular reflections can add so much to the visual complexity at road works that drivers may find it difficult to interpret the scene and find their way through.

That is certainly the case. Road works are often complex in themselves involving lane changes and the use complex additional equipment for warning and guidance such as temporary markings, temporary signs, warning lights on road signs, sequential running lights, flashing arrows, warning lights on vehicles, temporary work lighting etc. The additional light sources, and even retroreflecting surfaces, may all cause reflections in the road surface and add to the visual complexity.

It is recommended that:

- warning lights, in particularly when low mounted such as sequential running lights, are regulated so that the luminous intensity at night is not higher than needed
- luminaires used for work lighting are of strong cut-off, preferably with plane horizontal apertures, so that they don’t cause reflections at the approach to road works
- retroreflecting surfaces, in particular when mounted low such as directional marker plates, are not of unnecessarily strong retroreflection.

It is also recommended that the road surface is inspected prior to establishing the road work in order to assess if it may possibly be of a very high specular reflection. As portable instruments cannot be expected to be available, the only means are to judge the texture, the polishing of surfaces materials, and to inspect visually if the reflection of light sources or the sky indicates very high specular reflection.

If the road surface is judged to be of very high specular reflection it may be considered if effects of specular reflections can be reduced by particular means, for instance by avoiding the use of some light sources or changing their positions.

7.5 Literature:

Light & Optics note No. 2, 1990, “A model for the specular reflection of road surfaces”.

“Spegling i våta beläggningar, Störande ljus vid vägarbeten om natten” by Sara Nygårdhs, 2005.

EN 1436:2007, “Road marking materials - Road marking performance for road users.

CIE 144:2001, “Road surface and road marking reflection characteristics”.

8 Summary of results and discussions from field tests with stationary road works on a motorway

In the final stage of the project an expert group made evaluations of temporary traffic controls for a stationary motorway road works that was set up on a closed part of E6 outside Varberg (see figure 8.1 below). The expert group consisted of 10 persons, most of them coming from the project group.

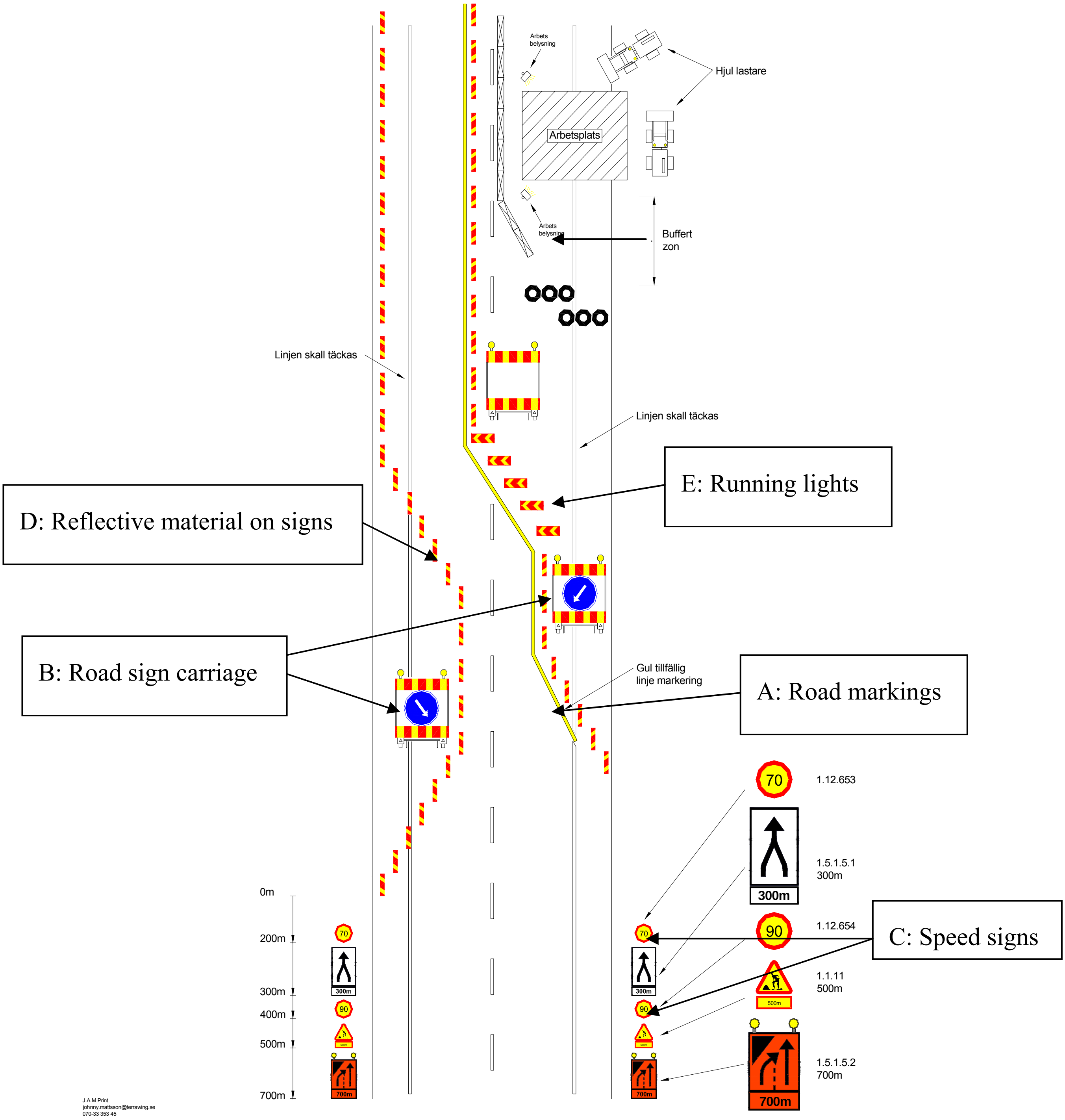

Figure 8.1: Sketch of the work site in the field tests on E6.

8.1.1 Results from assessments

A number of different scenarios, i.e. different combinations of traffic control components, were assessed by the experts while driving past the work zone. The experts made a subjective evaluation of the visual guidance and the degree of glare. The components that were varied are presented in the table below.

Table 8.1 The traffic control components and the different alternatives that were assessed in the field test.

Component	**Alternative**	
	1	**2**
A Road marking	Ordinary white road marking remaining within work zone	Ordinary white road marking covered within work zone
B Road sign carriage at the chicane	Only signs	Enhanced with flashing arrow
C Speed signs	Ordinary signs	Variable illuminated signs with recommended speed
D Type of reflective material on signs	Yellow (standard)	Yellowish-green (fluorescent)
E Yellow running lights at the diversion before the work zone	Without	With

There was in general a quite large consensus concerning the experts' assessments and stated preferences. The preferred alternatives of the different components are presented and commented below.

A: No preference

Normally the ordinary white road marking that is within the road works zone should be covered. This is however not always done which could mean a safety risk if the driver when driving in the dark is focused on the road marking and thereby not sufficiently observant on the diversion past the road work site.

In this case however, the other traffic control devices, i.e. the signs and the different flashing lights, where so dominant that it was even not noticed by all experts that any change was done concerning the road markings.

B: Alternative 1

Concerning the type of speed sign, i.e. ordinary sign or variable illuminated sign, all experts preferred the illuminated signs.

The speed signs don't have so much to do with the visual guidance. However, it is of great importance for the traffic safety that the drivers reduce their speed when approaching and passing a road work site.

To achieve a sufficient reduction speed limit signs are used as well as other traffic controlling/calming arrangements such as chicanes that forces the driver to reduce the speed.

It is important that the drivers are really made aware of the current speed limit. The variable illuminated signs were considered to help to draw the drivers' attention to the present speed limit.

C: Alternative 1

The experts generally preferred the carriage with signs only to carriage enhanced with flashing arrow. The flashing arrows were equipped with photocells for automatic reduction of luminous intensity, but the obtained reduction (up to 60 % of nominal effect) was far from sufficient in order for the flashing arrows not to be perceived as too glaring.

The main objective for using flashing arrows is to make the road users aware that they are approaching a road works site and should be prepared to certain redirection of the traffic as well as a reduced speed limit. The flashing arrows should be observed at a far distance in order to admit sufficient time for the drivers to react and respond to the information. This in turn means that the required light intensity by necessity is rather high, and can cause disturbing glare at closer distance.

It should be further investigated at what kinds of road works flashing arrows are suitable/necessary to use and in such cases the adequate light intensity and number of flashing arrows as well as the best positions for these.

If the flashing arrows are to be used for visual guidance the luminous intensity has to be reduced considerably.

D: Alternative 2

The majority also stated that they preferred the signs with the yellowish-green fluorescent reflective material to the ordinary yellow. The others didn't experience any difference. Since the fluorescent property has no effect other than during dusk, dawn or in foggy conditions it was mostly the higher quality of the reflective material that influenced the assessment.

E: Alternative 2

The majority of the experts stated that they preferred that yellow running lights were used at the diversion. The yellow running lights give the driver a more distinct visual guidance.

The general experience from the tests was otherwise that the number of yellow flashing lights should be reduced as much as possible.

In general it may also be assumed that the effective luminous intensity for all flashing lights on a work site should be about the same so that none of the lights are too dominant and thereby perceived as disturbing.

8.1.2 Literature

Ihs, Anita and Augdal, Arve (2008): Störande ljus vid vägarbeten om natten. Fältförsök på E6 norr om Varberg 19-20 april 2007. VTI Notat 24-2008. Statens väg- och transportforskningsinstitut, Linköping.

9 Concluding remarks

This project has mainly focussed on how to reduce the adverse effects of glare from different light sources that may occur in conjunction with road works during night. The main sources were identified as

- Yellow flashing lights
- Work zone illumination
- Headlights on opposing traffic
- Specular reflection in wet surfaces

Each of these sources have been studied separately within the project and recommendations have been developed that should be helpful when planning road works at night.

Today it could generally be said that the yellow flashing lights that are used at road work sites are too strong during night and in dusk, but too weak during day.

Based on the results from the project it can be concluded with great certainty that one definitely should use the new techniques/materials (e.g LED based flashing lights) to enable further regulation of the flashing lights luminous intensities.

Since the technical development in this area has gone forward beyond the frames of what is allowed according to the EN-standard (EN 12352) that regulates the requirements for flashing/warning lights, it can also be further concluded that there is a need for an update of this standard. Undesired trade barriers would thereby be avoided.

However, during the project several other issues have also been under discussion. In the field tests in Varberg (Chapter 8) a number of other elements were included in the assessment. One could briefly say that providing early and direct information is one of the fundamentals when the driver is approaching the road works site. Another rather obvious conclusion is that the road manager has to be unambiguous in his message to the driver, i.e. the guidance through different traffic control arrangements has to be chosen with care. There should not be too many different messages and one could for example often clearly notice that the fewer flashing lights that were used the clearer the guidance tended to become.

To really achieve the best possible and safest visual guidance for the driver, as well as the best possible safety and working environment for the road workers, it is important to carry out further studies on the total traffic control arrangement and the interaction/interference between all the different elements including flashing/warning lights, work site illumination, signs, road markings, etc.

Vägverket

Norwegian Public
Roads Administration

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