REFLECTION PROPERTIES OF ROAD SURFACES IN HEADLIGHT ILLUMINATION

Dependence on measuring geometry

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PREFACE

The investigation is a part of the research plan outlined in Mörkertrafik report No. 3 concerning optical and visual conditions on roads without fixed lighting.

The investigation gives, on the basis of measurements supported by model considerations, an account of the influence of the measuring geometry on the specific luminance of road surfaces. The measuring geometries are representative of the situation of illumination by the drivers own headlights.

Although the findings represented here are well suited for application purposes, a general instruction for this, including a standard measuring geometry for portable instruments, must wait for the completion of a similar investigation on road markings.

The investigation is carried out by the National Swedish Road and Traffic Research Institute (VTI) and the Danish Illuminating Engineering Laboratory (LTL) within the Nordic Research Cooperation for Night Traffic.

In this cooperation participates:
- The Danish Illuminating Engineering Laboratory (LTL) - Denmark
- The Road Directorate (VD-DK) - Denmark
- Road and Waterways Administration (VVS) - Finland
- The Norwegian Road Administration (VO-N) - Norway
- The Norwegian Research Institute for Electricity Supply (EFI) - Norway
- The National Swedish Road and Traffic Research Institute (VTI) - Sweden
The National Swedish Road Administration (VV)
- Sweden

The activities are co-ordinated by a group (co-ordination group), presently composed by:

- Kai Sørensen (LTL)
- Jørgen Haugaard (VD-DK)
- Pentti Hautala (VVS)
- Hans-Henrik Bjørset (EFI)
- Torkild Thurmann-Moe (VD-N)
- Kåre Rumar (VTI)
- Karl-Olov Hedman (VV)

This investigation has been organized by a project group with the participation of Sven-Olof Lundkvist (VTI), Gabriel Helmers (VTI), Kai Sørensen (LTL), Peder Øbro (LTL), Erik Randrup Hansen (LTL) and Axel Bohn as a consultant for the Danish Road Laboratory.

The co-ordination group has studied and approved the contents of the report.
ABSTRACT

Title: Reflection properties of road surfaces in headlight illumination - dependence on measuring geometry

Publisher: Nordic Research Co-operation for Night Traffic. Report No. 4, 1982. (The report can be obtained from the National Swedish Road and Traffic Research Institute, S-581 01 LINKÖPING, Sweden).

This investigation concerns the dependence of the geometry on the specific luminance of road surfaces in headlight illumination. The geometries considered are representative for the illumination of the road surface by the drivers own headlights.

The investigation comprises 10 road samples, each measured in 51 geometries both in dry and a humid condition. For the measurements is used an existing laboratory equipment, which has been modified and supplied with a semi-automatic data-registration.

The analysis of the data is based on model considerations of the reflection, leading to expressions for the influence of the geometry. The expressions are essentially confirmed by the analysis.

It is suggested, that for application purposes a standard measuring geometry is selected, as the specific luminance for other geometries can be estimated by the expressions.

A standard measuring geometry will be proposed later, when a similar investigation on road markings is completed.
**RESUMÉ**

Titel: Reflexionsegenskaper hos vägbeläggningar i strålkastarbelysning - mätgeometrins inverkan.

Utgivare: Nordiskt forskningssamarbete rörande synbetingelser i mörkertrafik. Rapport nr. 4, 1982. (Rapporten kan bestellas hos Statens väg- och trafikinstitut, S-581 01 LINKÖPING, Sverige.)

Denna undersökning avser de geometriska förhållandenas inverkan på den specifika luminansen hos vägbeläggningar i strålkastarbelysning. De geometriska förhållandena svarar mot den situation där vägbeläggningen belyses av bilistens egna lyktor.

Undersökningen omfattar 10 vägprover, som alla har mätts i 51 geometrier, både i torrt och i ett fuktigt tillstånd. Till mätningarna har använts en befintlig laboratorieutrustning, som modifierats och försetts med en halvautomatisk dataregistrering.

Analysen av mätresultaten baseras på modellbetraktelser av reflexionen, vilka lett till formeluttryck för geometrins inverkan. Dessa formeluttrycks giltighet bekräftas i det väsentligaste av analysen.

Det föreslås att man väljer ut en standardiserad mätgeometri för tillämpning, då den specifika luminansen för andra geometrier kan uppskattas då man använder formeluttrycken.

En standardiserad mätgeometri kommer senare att föreslås när en liknande undersökning rörande vägmarkeringar är färdig.
Otsikko: Valonheittimellä valaistun tienpäällyysteen heijastusominaisuudet – mittausgeometrian vaikutukset.

Julkaisija: Pohjoismainen pimeän liikenteen näköedellytyksä tutkiva yhteistyöryhmä. Raportti no. 4, 1982. (Raporttie voi tilata osoitteella Statens väg- och trafikinstitut, S-581 01 LINKÖPING, Sverige)

Tässä tutkimuksessa selviteään geometristen olosuhteiden vaikutusta tienpäällyysteen ominaisvaloisuuteen (eli spesifiseen luninanssiin), kun päällystettä valaistaan valonheittimellä. Geometriset olosuhteet vastaavat tilannetta, jossa kuljettaja tarkastelee oman autonsa ajovalojen valaisemaa tietää.

Tutkimus käsittää 10 tienäytettä, joilla kullakin on suoritettu yhteensä 51 mittauta geometriaa vaihdellen sekä kuivan tien että märän tien olosuhteissa. Mittauksiin käytettiin saatavissa ollutta laboratoriokalustoa, jota muunneltiin ja varustettiin puoli-automaatallisella tulostenrekisteröinnillä.


Tutkimuksen perusteella ehdotetaan sovellettavaksi käytetään standardisoitua mittausgeometriaa. Tällöin kyetään muiden geometrioiden ominaisvaloisuudet arvioimaan yhtälöiden avulla.

Ehdotus tällaiseksi standardigeometriaksi tullaan tekemään myöhemmin, sen jälkeen kun vastaava ajoratamerkintöja koskeva tutkimus on valmis.
1. **INTRODUCTION**

By Sven-Olof Lundkvist, VTI

This investigation concerns the dependence of the geometry on the specific luminance of road surfaces in headlight illumination. The geometries considered are representative for the illumination of the road surface by the drivers own headlights.

Reflection properties of a road surface are very important in night time traffic. So far, most studies concerning reflection properties, have dealt with roads with stationary lighting. However, these properties of the road surface are as important on unlit roads as on roads with public lighting. The driver has to detect an obstacle on or very close to the roadway, at safe distances, i.e. mostly the luminance pattern of the background shall be as uncomplicated as possible. Further, obstacles must have a high contrast against the background. On unlit roads it is also important that the road surface with its road markings give the driver an acceptable visual guidance.

Our knowledge of the reflection properties of an unlit road surface - dry or humid - and how these properties influence the task of the driver is today too small; the essential is rendered in Mörkertrafik report No. 3, chapter 3.2 (Sørensen, 1980) and concerning detection of obstacles on unlit roads in VTI report No. 202 (Helmers & Ytterbom, 1980).

Today a good method of measurement is missing for specular reflection as well as for retroreflection. The purpose of this work is to investigate empirically if earlier theories on retroreflection of road pave-
ments are according to reality. These theories deal with the specific luminance dependence of the measuring geometry and of the texture of the road surface. They are valid for one light-source only, but as additivity applies, they are useful also in the situation of a car driver. From the theories a mathematical model for non-retroreflective surfaces can be built up.

Physical measurements under different geometrical conditions have therefore been carried out. Consideration has been taken not only to observation- and illumination angles, but also the angle between the direction of observation and the direction of illumination in a horizontal plane, called the azimuthal angle.

In the study ten different road pavements were investigated. The specific luminance was measured in dry and humid, but not wet conditions.

Briefly, this report contains, in chapter 2, a description of the road samples, followed by definitions in chapter 3. In chapter 4 the equipment, which was used, is described. Measuring procedures and results will be found in chapter 5, followed by a description of how to apply the results onto measurement methods for the specific luminance.

Appendix A includes reflection tables for all ten pavements under the two conditions. The theories and mathematical models are described in Appendix B.

Reflection properties of retroreflective surfaces at similar geometrical conditions will be presented in a later report.
2. CHOICE OF ROAD SURFACE SAMPLES

The samples included in the investigation are 4 samples from Danish roads and 6 samples from Swedish roads. Those samples have been selected from the collection of road surface samples at LTL, on which the r-tables of LTL-report No. 10 were measured. The dimensions of the samples are 20 cm times 40 cm. Before the measurement they have been inspected to see if they were perfectly plane. If not plane, the top layer has been separated, planed out and re-based on 3 mm thick steelplates. The ten samples are described shortly in table 2.1 and presented on photos in figure 2.1.

<table>
<thead>
<tr>
<th>LTL No.</th>
<th>Type of light coloured stones</th>
<th>Size of aggregate, type</th>
<th>Country</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>35 % Calcined flint</td>
<td>0/3 mm, Thin asphalt carpet</td>
<td>DK</td>
</tr>
<tr>
<td>601</td>
<td>20 % Calcined flint</td>
<td>0/12 mm Asphalt concrete</td>
<td>DK</td>
</tr>
<tr>
<td>609</td>
<td>20 % Calcined flint</td>
<td>0/18 mm, Asphalt concrete</td>
<td>DK</td>
</tr>
<tr>
<td>460</td>
<td>13 % Synopal (4/8 mm) 13 % Calc. flint (5/8 mm)</td>
<td>0/8 mm, Asphalt concrete</td>
<td>S</td>
</tr>
<tr>
<td>617</td>
<td>Light granite</td>
<td>12/16 mm, Surface treatment</td>
<td>DK</td>
</tr>
<tr>
<td>87</td>
<td>Quartzite</td>
<td>0/16 mm, Asphalt concrete</td>
<td>S</td>
</tr>
<tr>
<td>90</td>
<td>Diabase (0/12 mm) Gneiss (0/12 mm)</td>
<td>0/12 mm, Asphalt concrete</td>
<td>S</td>
</tr>
<tr>
<td>176</td>
<td>Swedish granite</td>
<td>0/8 mm, Asphalt concrete</td>
<td>S</td>
</tr>
<tr>
<td>177</td>
<td>Swedish granite</td>
<td>0/12 mm, Asphalt concrete</td>
<td>S</td>
</tr>
<tr>
<td>182</td>
<td>Precoated chippings of Sw. granite</td>
<td>Topeka asphalt concrete (ABS II)</td>
<td>S</td>
</tr>
</tbody>
</table>
Tabell 2.1 Kort beskrivning av samplerna

<table>
<thead>
<tr>
<th>LTL Nr</th>
<th>Typ av ljust stenmaterial</th>
<th>Stenstorlek, typ</th>
<th>Land</th>
</tr>
</thead>
<tbody>
<tr>
<td>63</td>
<td>35 % calc. flintsten</td>
<td>0/3 mm, pulverasfalt</td>
<td>DK</td>
</tr>
<tr>
<td>601</td>
<td>20 % calc. flintsten</td>
<td>0/12 mm, asfaltbetong</td>
<td>DK</td>
</tr>
<tr>
<td>609</td>
<td>20 % calc. flintsten</td>
<td>0/18 mm, asfaltbetong</td>
<td>DK</td>
</tr>
<tr>
<td>460</td>
<td>13 % synopal (4/8 mm)</td>
<td>0/8 mm, asfaltbetong</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>13 % calc. flintsten (5/8 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>617</td>
<td>ljus granit</td>
<td>12/16 mm, ytbehandling</td>
<td>DK</td>
</tr>
<tr>
<td>87</td>
<td>kvartsit</td>
<td>0/16 mm, asfaltbetong</td>
<td>S</td>
</tr>
<tr>
<td>90</td>
<td>diabas (0/12 mm)</td>
<td>0/12 mm, asfaltbetong</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>gnejs (0/12 mm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>176</td>
<td>svensk granit</td>
<td>0/8 mm, asfaltbetong</td>
<td>S</td>
</tr>
<tr>
<td>177</td>
<td>svensk granit</td>
<td>0/12 mm, asfaltbetong</td>
<td>S</td>
</tr>
<tr>
<td>182</td>
<td>skärvor av svensk granit *</td>
<td>Topeka (ABS II)</td>
<td>S</td>
</tr>
</tbody>
</table>

To the samples the following comments apply.

Samples 63, 601 and 609 are Danish road surfaces with light coloured stones of varying size. Sample 63 is special in the meaning that the stones are not protruding above the surface of the sample.

In sample 460 there are two types of stone materials. Those stones are protruding above the surface of the sample, which makes it rough.

Sample 617 is a surface treatment with rather large chippings of a light coloured type of granite.

Of all the Swedish samples all except No. 90 are common on public roads. Sample 90 is rather rare although there are no light stones in it; it contains almost black gneiss and diabas which is speckled but rather dark. Sample 87 is taken from a 9 year old surface and therefore more worn than the others. Samples 175 and 177 are very common on Swedish roads and contain
Swedish granite.

Sample 182, ABS, is mainly used on roads with heavy traffic. ABS is more durable than an ordinary asphalt concrete. All white precoated stones are here concentrated at the surface of the pavement. In this particular sample there is a relative small amount of those stones, so that the black matrix dominates the visual perception at large angles of observation.
Figure 2.1 The appearance of the samples. Below each sample is the LTL no. (see table 2.1) and the SL-value in the geometry of $\alpha=1.37^\circ$, $\varepsilon=0.74^\circ$, $\beta=180^\circ$ and dry condition (mcd/m²)/lux.

Figur 2.1 Vägytornas utseende. Under varje sample har angivits dess LTL-nr (se tabell 2.1) och SL-värde i geometrin $\alpha=1.37^\circ$, $\varepsilon=0.74^\circ$, $\beta=180^\circ$ vid torr vägbana (mcd/m²)/lux.
3. DEFINITIONS AND NOTATIONS

The relative amount of light of a road surface reflected back to the eyes of the driver in vehicle headlight illumination on unlit roads can be described by the specific luminance (SL) of the road surface. The concept of specific luminance is defined as follows

\[ SL = \frac{L}{E} \text{ (cd/m}^2\text{)/lux} \]  

where \( L \) is the luminance (cd/m\(^2\)) of the road surface at the point \( P \), and \( E \) is the illuminance (lux) on a fictive plane situated at the point \( P \) and orientated perpendicular to the direction of illumination.

The specific luminance of a surface is dependent on the geometry of measurement, defined by the angles \( \phi \), \( \alpha \) and \( \beta \) in figure 3.1 below.

![Figure 3.1](image)

**Figure 3.1** Definition of parameters determining the geometry of observation and illumination

Definition av parametrar som bestämmer observations- och belysningsgeometrin.
Denotations in figure 3.1:

ε = illumination angle
α = observation angle
ς = azimuthal angle
ς' = supplemental azimuthal angle (=180°-β)
H₀ = observation height
Hₜ = illumination height
D₀ = distance of observation
Dₜ = distance of light source
Dₜ = transverse displacement of headlight
P = point of measurement

Beteckningar i figur 3.1:

ε = belysningsvinkel
α = observationsvinkel
β = azimuthalvinkel
β' = azimuthalvinkels supplementvinkel (=180°-β)
H₀ = observationshöjd
Hₜ = belysningshöjd
D₀ = observationsavstånd
Dₜ = belysningsavstånd
Dₜ = sidoförskjutning mellan observatör och ljuskälla
P = mätpunkt

In this study the angle of observation has been varied within the range of 0.57° to 8.53°, the angle of illumination between 0.37° and 3.72° and the azimuthal angle between 180° and 185°. The combinations of those angles have been chosen so that they simulate realistic distances of observation and illumination and an adequate displacement between observer and light source.

This means that the azimuthal angle adopted values near 180°. The specific luminance is then often called retroreflection. This concept, however, indicates that the luminance is due to retroreflective
elements of a surface, which is not the case here. Therefore, the more general concept of specific luminance (SL) is used in this report. However, one has to emphasize that this is no internationally accepted concept.
4. MEASURING EQUIPMENT

The measurements of specific luminance have been carried out with a Pritchard Photometer Model 1980. The light source was a projector with a halogen bulb.

To adjust the measuring geometry properly, the photometer and projector were mounted in a special type of goniometer, which has a quality of being able to vary the illumination and observation angles continuously. The azimuthal angle on the other hand could vary in 5 discrete values. This was made possible with a special arrangement of mirrors. The goniometer is presented in figure 4.1. The projector was equipped with a slide giving a rectangular illuminated field at the sample. Further it had an iris diaphragm giving an aperture of about 8'. The photometer was also equipped with an iris diaphragm giving it an aperture of about 10'. The shape of the measuring field was rectangular with the size 3.3' x 21'.

The sample was placed on a special sample holder which could be displaced horizontally (figure 4.2). This made it possible to measure as many values as were needed to get an adequate mean value of the SL of each sample. The sample holder was also adjustable in order to get the sample absolutely horizontally located.

All samples were measured in dry and a humid condition. Before the measurement for the dry condition the sample was properly cleaned. The humid condition was created by the following procedure: First the sample was wet with ordinary water containing detergent (to reduce surface tension). After that it was wiped off twice with a sponge. In that way a humid condition which was stable for about 15 minutes was attained.
All data were stored on paper-tape for later computer analysis.

Figure 4.1 Goniometer equipment. To the left is seen the photometres (1) and the light-source (2). Simulated distances can be varied by moving the arms (3) and (4) up and down independently, and the transverse distance by a turning of the mirror (5). To the right is shown the sample holder, which is adjustable in all directions.

Goniometerutrustning. Till vänster ses luminansmätaren (1) och ljuskällan (2). Simulerade avstånd kan varieras genom att föra armarna (3) och (4) upp och ned oberoende av varandra samt sidoförskjutningen genom att vrida spegeln (5). Till höger ses sample-bordet, som är justerbart i alla riktningar.
Figure 4.2 The adjustable sample holder

Det justerbara sample-bordet
5. MEASUREMENTS
By Peder Øbro and Kai Sørensen, LTL

5.1 Measuring geometries – reflection table
The measuring geometries are defined by a number of combinations of the illumination angle, $\varepsilon$, the observation angle, $\alpha$ and the azimuthal angle, $\beta$. See fig. 3.1.

The combinations of the angles $\varepsilon$ and $\alpha$ were chosen to simulate the geometries shown in fig. 5.1. These angles are shown in table 5.1 also. It is remarked that whenever the letter D is used, this implies that the distances of illumination and observation are assumed to be equal, i.e.: $D = D_h = D_o$.

The azimuthal angle, $\beta$ should preferably be chosen also on the basis of simulated geometries of the vehicle. A convenient measure is the distance of the headlight from the vertical plane containing the direction of observation. This distance is in the following called the transverse distance of the headlight, $D_t$ and is defined as shown in fig. 5.2. In fig. 5.2 is introduced also the angle, $\beta'$, which is supplemental to the azimuthal angle, $\beta$ ($\beta' = 180^\circ - \beta$).

When considering transverse distances, $D_t$ between 0 m and 1.5 m, this undoubtedly covering the geometry of most vehicles, the angle $\beta'$ should vary according to the distance, $D$ as shown in table 5.2.

However, table 5.2 contains 14 different values of the angle $\beta'$, while the mirror arrangement for the setting of this angle allows the use of only 5 mirrors at a time, see fig. 4.1. It is possible to set all of the angles of table 5.2 by means of the mirror arrangement, but only in a tedious procedure involving adjustments of the mirrors.
Figure 5.1 Combinations of distance on the road, D, headlight mounting height, \( H_h \), and observer eye height, \( H_o \), simulated in the measurements.

<table>
<thead>
<tr>
<th>( H_o )</th>
<th>1.5 m</th>
<th>1.2 m</th>
<th>1.0 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H_h )</td>
<td>0.65 m</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Distance, \( D \) = 10 m, 15 m, 30 m, 50 m, 75 m, and 100 m

Table 5.1 Variation of the illumination angle, \( \varepsilon \) and the observation angle, \( \alpha \) with the distance on the road, \( D \). The headlight mounting height, \( H_h \), is assumed to be 0.65 m, while the observer eye height, \( H_o \), is either 1 m, 1.2 m or 1.5 m.

<table>
<thead>
<tr>
<th>Distance, ( D )</th>
<th>( 10 ) m</th>
<th>( 15 ) m</th>
<th>( 30 ) m</th>
<th>( 50 ) m</th>
<th>( 75 ) m</th>
<th>( 100 ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination angle, ( \varepsilon )</td>
<td>3.72°</td>
<td>2.48°</td>
<td>1.24°</td>
<td>0.74°</td>
<td>0.50°</td>
<td>0.37°</td>
</tr>
<tr>
<td>Observation angle, ( \alpha ) at observer eye height, ( H_o ) of:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 m</td>
<td>5.71°</td>
<td>3.81°</td>
<td>1.91°</td>
<td>1.15°</td>
<td>0.76°</td>
<td>0.57°</td>
</tr>
<tr>
<td>1.2 m</td>
<td>6.84°</td>
<td>4.57°</td>
<td>2.29°</td>
<td>1.37°</td>
<td>0.92°</td>
<td>0.69°</td>
</tr>
<tr>
<td>1.5 m</td>
<td>8.53°</td>
<td>5.71°</td>
<td>2.86°</td>
<td>1.72°</td>
<td>1.15°</td>
<td>0.86°</td>
</tr>
</tbody>
</table>

Variation af belysningsvinklen, \( \varepsilon \) og observationsvinklen, \( \alpha \) med afstanden målt på kørebanen. Forlygtens monteringshøjde antages at være 0,65 m, mens observatørens øjenhøjde er enten 1 m, 1,2 m eller 1,5 m.
The geometry of illumination and observation as projected onto the road surface. The transverse distance of the headlight, $D_t$, is the distance of the headlight from the vertical plane containing the direction of observation. The angle, $\beta'$, is defined as the supplemental to the azimuthal angle, $\beta$. 

$$ \beta' = 180^\circ - \beta $$

$$ D_t = D_h \cdot \sin \beta' \equiv D_h \cdot \beta' \quad (\beta' \text{ in radians}) $$

$$ \beta' = \sin^{-1} \left( \frac{D_t}{D_h} \right) \equiv D_t/D_h \quad (\text{radians}) $$

It was decided, therefore, to use a procedure in which SL-values for the $\beta'$ indicated in table 5.2 should be obtained by interpolations in a set of measurements that include only 5 different $\beta'$. 

Figure 5.2
This set of values of $\beta'$ were chosen to $0^\circ$, $1^\circ$, $2^\circ$, $3.5^\circ$ and $5^\circ$. At each simulated distance (at each $\varepsilon$) a subset of two to four of these $\beta'$ values were further chosen on the basis of two considerations. Firstly, the subset should approximately cover the range of $\beta'$ given in table 5.2 and, secondly, for reasons of measuring economy each subset should be as small as possible.

Table 5.2 Variation of the angle $\beta'$ supplemental to the azimuthal angle with the transverse distance of the headlight, $D_t$ and the distance of the road, $D$.

<table>
<thead>
<tr>
<th>Distance, $D$ at $H_h = 0.65$ m</th>
<th>$10$ m</th>
<th>$15$ m</th>
<th>$30$ m</th>
<th>$50$ m</th>
<th>$75$ m</th>
<th>$100$ m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination angle, $\varepsilon$</td>
<td>$3.72^\circ$</td>
<td>$2.48^\circ$</td>
<td>$1.24^\circ$</td>
<td>$0.74^\circ$</td>
<td>$0.50^\circ$</td>
<td>$0.37^\circ$</td>
</tr>
<tr>
<td>Supplemental, $\beta'$ to the azimuthal angle at transverse distance of headlight, $D_t$:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$0$ m</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
<td>$0^\circ$</td>
</tr>
<tr>
<td>$0.5$ m</td>
<td>$2.87^\circ$</td>
<td>$1.91^\circ$</td>
<td>$0.95^\circ$</td>
<td>$0.57^\circ$</td>
<td>$0.38^\circ$</td>
<td>$0.27^\circ$</td>
</tr>
<tr>
<td>$1$ m</td>
<td>$5.74^\circ$</td>
<td>$3.82^\circ$</td>
<td>$1.91^\circ$</td>
<td>$1.15^\circ$</td>
<td>$0.76^\circ$</td>
<td>$0.57^\circ$</td>
</tr>
<tr>
<td>$1.5$ m</td>
<td>$8.63^\circ$</td>
<td>$5.74^\circ$</td>
<td>$2.87^\circ$</td>
<td>$1.72^\circ$</td>
<td>$1.15^\circ$</td>
<td>$0.85^\circ$</td>
</tr>
</tbody>
</table>

The choice of subsets of values of $\beta'$ is shown in table 5.3. It is seen that a reproduction of the $\beta'$ angles of table 5.2 can in most cases be based on interpolation, but that extrapolation is required for some geometries.

The total set of measuring geometries is obtained by taking all possible combinations of the geometries of table 5.1 and 5.3. This total set is illustrated in
table 5.4, which also shows the format of a reflection table with 51 positions.

It appears from a comparison of table 5.1 to table 5.4 that the combination \((\alpha = 0.86^\circ, \varepsilon = 0.37^\circ)\) has been replaced by \((\alpha = 0.76^\circ, \varepsilon = 0.37^\circ)\). This was done in order to simplify the measuring procedure, and has the consequence that the SL for \((D = 100 \text{ m}; H_0 = 1.5 \text{ m})\) has to be based on an extrapolation. In recent measurements on road markings this geometry has been included directly in the measuring programme.

### Table 5.3

<table>
<thead>
<tr>
<th>Distance, D at (H_n = 0.65 \text{ m})</th>
<th>10 m</th>
<th>15 m</th>
<th>30 m</th>
<th>50 m</th>
<th>75 m</th>
<th>100 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Illumination angle, (\varepsilon)</td>
<td>3.72°</td>
<td>2.48°</td>
<td>1.24°</td>
<td>0.74°</td>
<td>0.50°</td>
<td>0.37°</td>
</tr>
<tr>
<td>Set of supplemental azimuthal angles, (\beta')</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0°</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>1°</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>2°</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.5°</td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5°</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The format of the reflection table thus covers those geometrical situations that appear from fig. 5.1, with the further addition that \(D_t\) can be up to appr. 1.5 m. As the angles are the fundamental parameters, the table does cover also all geometries, whose relative proportions are within the ranges of the
above-mentioned situations. These ranges of relative proportions are:

\[
1.54 \, H_h \leq H_o \leq 2.31 \, H_h \\
|D_t| \leq 2.31 \, H_h \\
15.4 \, H_h \leq D_o \quad \text{and} \quad D_h \leq 154 \, H_h
\]

Therefore, the format of the reflection tables does in fact cover a wide range of geometries.

5.2 Measuring procedures and data handling

Each of the ten samples are successively placed in the measuring equipment, accurately aligned and then exposed to the full measuring program, first for the dry and then for the humid condition.

In the measuring program the angles were set in a succession starting in the upper left corner and going down to the right lower corner of the reflection table of table 5.4. This succession was chosen so that the values of \( \xi \) and \( \alpha \) were set only once, while the easier setting of the values of \( \beta' \) was carried out repeatedly. At each combination of angles 18 readings were taken for reasons explained below.

The measuring field of 3.3' x 21' results at the actual measuring distance of 3.6 m in a measuring field, whose width is 2.2 cm. The length varies between 35 cm at the smallest \( \alpha \) of 0.57° to 2.3 cm at the largest \( \alpha \) of 8.53°.

At the largest \( \alpha \) of 8.53° the measuring field is, therefore, only 2.2 x 2.3 cm² = 5.1 cm². As a total measuring field of appr. 100 cm² is desirable, the sledge of the sample holder was used to move the sample in 9 steps in the longitudinal direction and 2 steps in the transverse direction. In this way the number of 18 readings results in a total measuring field of appr. 5 x 20 cm² = 100 cm².
<table>
<thead>
<tr>
<th>θ</th>
<th>α</th>
<th>0.57°</th>
<th>0.69°</th>
<th>0.76°</th>
<th>0.92°</th>
<th>1.15°</th>
<th>1.37°</th>
<th>1.72°</th>
<th>1.91°</th>
<th>2.29°</th>
<th>2.86°</th>
<th>3.81°</th>
<th>4.57°</th>
<th>5.71°</th>
<th>6.84°</th>
<th>8.53°</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.37°</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>0.50°</td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.74°</td>
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<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
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<td></td>
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</tr>
<tr>
<td>1.24°</td>
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<td>x</td>
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<td>x</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.48°</td>
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<td></td>
<td></td>
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<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3.72°</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

Table 5.4 Format of reflection table containing 51 positions.

Format af refleksionstabel, som indeholder 51 værdier.
In order to handle this large number of readings safely and within a reasonable time, the sledge was equipped with a trigger mechanism, so that the movement of the sledge (by hand) triggers the reading and the punching of the data on papertape.

For practical reasons this measuring procedure was used for all of the different values of \( \alpha \). The full measuring program, therefore, results in a papertape with 18 times 51 values to be sorted out in a subsequent computer run.

In this handling of the data, each \( \text{SL} \) was computed as a weighted average of the 18 readings. For geometries of the largest \( \alpha \) of 8.53°, the individual measuring fields do not overlap and all readings are given identical weights in the calculation of the average.

For decreasing \( \alpha \) the individual measuring fields will overlap to an increasing extent, and, therefore, the weights will have to be graduated in order to give all parts of the total measuring field an equal contribution to the average \( \text{SL} \).

Further, at small \( \alpha \) some of the readings will correspond to individual measuring fields, that cannot be safely contained within the surface of the sample. These readings have to be disregarded, i.e.: their weights are set to zero.

The weights were computed and fed into a computer program SLMAL, which reads the tapes, computes the \( \text{SL} \)-values of the reflection table, checks the consistency of the readings and prints the reflection table and information regarding the result of the checking.

The total amount of measuring data consists of two reflection tables, one for the dry and one for the
humid condition for each of the ten road samples described in chapter 2. An example of a reflection table is shown in table 5.5.

These tables were stored in a permanent file and further computer programs were successively designed to allow the analyses described in the following sections. The tables are shown in Appendix A.

**Table 5.5** An example of a computer-printed reflection table (sample No. 601 in dry condition).

Et eksempel på en EDB-udskrevet refleksionstabel (prøve nr. 601 i tør tilstand).

<table>
<thead>
<tr>
<th>ALFA</th>
<th>EPSI</th>
<th>BETA</th>
<th>57</th>
<th>69</th>
<th>.76</th>
<th>.92</th>
<th>1.15</th>
<th>1.37</th>
<th>1.72</th>
<th>1.91</th>
<th>2.29</th>
<th>2.96</th>
</tr>
</thead>
<tbody>
<tr>
<td>.37</td>
<td>.00</td>
<td>10.25</td>
<td>20.20</td>
<td>18.00</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td>8.20</td>
<td>13.85</td>
<td>15.35</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>.50</td>
<td>.00</td>
<td>-----</td>
<td>-----</td>
<td>21.00</td>
<td>18.00</td>
<td>14.00</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td>-----</td>
<td>-----</td>
<td>13.65</td>
<td>15.25</td>
<td>13.55</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>.74</td>
<td>.00</td>
<td>-----</td>
<td>-----</td>
<td>-----</td>
<td>23.05</td>
<td>18.35</td>
<td>15.94</td>
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<td>I</td>
<td>I</td>
<td>I</td>
<td>I</td>
</tr>
<tr>
<td>1.00</td>
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<td>-----</td>
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<td>17.05</td>
<td>16.00</td>
<td>14.09</td>
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</tr>
<tr>
<td>2.00</td>
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<td>-----</td>
<td>-----</td>
<td>20.30</td>
<td>16.16</td>
<td>14.48</td>
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<td>I</td>
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<td>I</td>
</tr>
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<td>------</td>
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<td>------</td>
</tr>
<tr>
<td>1.00</td>
<td></td>
<td>-----</td>
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</tr>
<tr>
<td>2.00</td>
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</tr>
<tr>
<td>3.50</td>
<td></td>
<td>-----</td>
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<td>-----</td>
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<td>------</td>
<td>------</td>
<td>------</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ALFA</th>
<th>EPSI</th>
<th>BETA</th>
<th>3.61</th>
<th>4.57</th>
<th>5.71</th>
<th>6.84</th>
<th>8.53</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.48</td>
<td>.00</td>
<td>22.43</td>
<td>19.41</td>
<td>15.54</td>
<td>I</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>2.00</td>
<td></td>
<td>22.78</td>
<td>18.97</td>
<td>15.63</td>
<td>I</td>
<td>I</td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td></td>
<td>19.50</td>
<td>18.30</td>
<td>14.86</td>
<td>I</td>
<td>I</td>
<td></td>
</tr>
<tr>
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<td>.00</td>
<td>-----</td>
<td>-----</td>
<td>20.12</td>
<td>18.10</td>
<td>15.19</td>
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</tr>
<tr>
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<td></td>
<td>-----</td>
<td>-----</td>
<td>21.54</td>
<td>17.65</td>
<td>15.11</td>
<td></td>
</tr>
<tr>
<td>5.00</td>
<td></td>
<td>-----</td>
<td>-----</td>
<td>18.49</td>
<td>16.28</td>
<td>15.99</td>
<td></td>
</tr>
</tbody>
</table>
5.3 General remarks to the measurements

It was attempted to use a straightforward presentation of the data as exemplified by the diagram of fig. 5.3. In this diagram the SL is given as a function of the simulated distance, \(D\) by means of curves for all six combinations of the three values of \(H_o\) and two values of \(D_t\).

It is seen, however, that a diagram of this type does not clearly show the influence of the parameters. For this reason the influence of the parameters is illustrated in the next sections by means of various types of diagrams.

Fig. 5.3 does illustrate, however, that the measured SL-values for \(H_o = 1\ m\) at \(D = 100\ m\) (\(\alpha = 0.57^\circ\)) are too uncertain to be useful.

In this geometry the measuring field is almost as long as the sample, when the surface is plane. Due to the surface texture of the sample the measuring field is often, in fact, elongated to the extent that it cannot be contained on the sample. The effect of this will depend on where precisely the center of the measuring field is placed on the sample, but the net result can be considered to be the above-mentioned uncertainty.

For these reasons the SL-values for \(H_o = 1\ m\) at \(D = 100\ m\) are excluded from the diagrams of the following sections.

The SL-values for \(H_o = 1.5\ m\) at \(D = 100\ m\) must, as stated in section 5.1 be obtained by extrapolation, using values for \(\alpha = 0.69^\circ\) and \(0.76^\circ\) to obtain a value at \(\alpha = 0.86^\circ\). This procedure results in a value, whose uncertainty is almost 3 times the uncertainty of the measured values. This increase in uncertainty was found to impair the usefulness of
Figure 5.3 Example of diagram (for sample No. 601), giving SL as a function of the simulated distance, D by means of curves for different combinations of \( H \) and \( D_T \). The measuring uncertainty for \( H = 1 \) m at \( D = 100 \) m (points marked by \( * \)) is large, while for \( H = 1.5 \) m at \( D = 100 \) m (points marked by \( ** \)) the extrapolation in \( \alpha \) causes a large uncertainty.

Eksempel på diagram (for vejprøve nr. 601), som viser SL som en funktion af den simulerede afstand, D med kurver for forskellige kombinationer af \( H \) og \( D_T \).

Måleusikkerheden er stor for \( H = 1 \) m ved \( D = 100 \) m (punkterne er markeret med \( * \)), mens den til grund liggende ekstrapolation i \( \alpha \) bevirker en stor usikkerhed for \( H = 1.5 \) m ved \( D = 100 \) m (punkterne er markeret ved \( ** \)).
the data for \( H_0 = 1.5 \) m at \( D = 100 \) m, and, therefore, these data are also excluded from diagrams using \( D \) as the abscissa. In other types of diagrams the SL-values for \( (\varepsilon = 0.50^\circ, \alpha = 0.76^\circ) \) are used, as they are in themselves correct.

In conclusion, for \( D = 100 \) m SL-values for \( H_0 = 1 \) m and \( 1.5 \) m are excluded, leaving only SL-values for \( H_0 = 1.2 \) m at this distance. SL-values corresponding to \( H_0 = 1 \) m at \( D = 100 \) m \( (\varepsilon = 0.37^\circ, \alpha = 0.57^\circ) \) are excluded from all diagrams, while the SL-values for \( (\varepsilon = 0.57^\circ, \alpha = 0.76^\circ) \) are used whenever possible.

5.4 Dry condition - influence of geometry

5.4.1 Influence of observer eye height

According to the model considerations of Appendix B, the influence of the observer eye height should, when \( D_t = 0 \), mainly be accounted for by the factor of geometry, \( f_{\text{geometry}} \), which is given by:

\[
f_{\text{geometry}} = \frac{H_h}{H_0} \text{ for } D_o = D_h = D
\]

Therefore, SL values for \( H_0 = 1 \) m and \( 1.5 \) m should be respectively 20 % higher and 20 % lower than SL values for \( H_0 = 1.2 \) m. This is tested in fig. 5.4, in which the ratios \( \text{SL}(H_0 = 1 \text{ m})/\text{SL}(H_0 = 1.2 \text{ m}) \) and \( \text{SL}(H_0 = 1.5 \text{ m})/\text{SL}(H_0 = 1.2 \text{ m}) \) are given as functions of \( D \) for all measurements, where \( D_t = 0 \).

Fig. 5.4 shows that the measurements of course deviate from the model considerations because of measuring uncertainties.

Apart from measuring uncertainties the ratios also seem to differ on the average somewhat less than 20 % from unity. This can be taken to indicate that texture of section B.5 is not completely independent of the observation angle, but does increase
Figure 5.4 Ratios $\frac{SL(H_0 = 1 \text{ m})}{SL(H_0 = 1.2 \text{ m})}$ and $\frac{SL(H_0 = 1.5 \text{ m})}{SL(H_0 = 1.2 \text{ m})}$ for $D_t = 0$ and dry samples.

Forholdene $\frac{SL(H_0 = 1 \text{ m})}{SL(H_0 = 1.2 \text{ m})}$ og $\frac{SL(H_0 = 1.5 \text{ m})}{SL(H_0 = 1.2 \text{ m})}$ for $D_t = 0$ tør tilstand af vejprøverne.
slowly with this angle. In the words of Appendix B, facets of a small inclination give a small, but measurable contribution to SL.

It is to be concluded, however, that $f_{\text{geometry}}$ accounts for the major part of the influence of the observer eye height (of $\alpha$).

5.4.2 Influence of distance
When $D_t = 0$, the influence of the observer eye height is accounted for by the factor $f_{\text{geometry}}$ as stated in the previous section. The remaining parameter, whose influence is to be investigated, is then the simulated distance on the road. It is sufficient to consider the influence of the distance for only one observer eye height.

Fig. 5.5 shows SL as a function of the distance for $H_0 = 1.2$ m and for all samples in the dry condition.

It is seen that for sample No. 460 SL increases with the distance, until $D = 50$ m where the SL-value remains appr. constant. This variation is explained by a variation in the average luminance coefficient, $\tilde{q}$, which is introduced in section B.3 of Appendix B.

This sample (No. 460) is a special asphalt concrete containing small (less than 2 mm), dark aggregates in a mixture with larger (4 to 8 mm) light coloured aggregates (Synopal and calcined flint in equal proportions). The surface, therefore, appears with white stones protruding somewhat from the dark matrix.

At short distances a part of the incident luminous flux falls on the dark matrix, and hence $\tilde{q}$ has a relatively small value. With increasing distance larger proportions of the luminous flux fall on the white stores, and from appr. 50 m and upwards all of the luminous flux falls on the white stones in the surface. Hence $\tilde{q}$
Figure 5.5 Ratios SL/SL(D = 50 m) for \(D_0 = 0\) and dry samples. For most of the samples the SL is roughly independent of the distance. For the samples indicated variations are caused by variations in \(q\) (No.s 460 and 63) or in \(f_{\text{texture}}\) (No. 617).

Forholdene SL/SL(D = 50) for \(D_0 = 0\) og tør tilstand af vejprøverne. For de fleste af prøvernes vedkommende er SL omtrent uafhængig af afstanden. For de angivne prøver skyldes variationerne enten variationer i \(q\) (nr. 460 og 63) eller i \(f_{\text{texture}}\) (nr. 617).
is expected to vary as the measured SL, and can explain the variation of SL.

Sample No. 63 has, on the other hand a fine-grained light coloured aggregate (0-3 mm calcined flint) mixed with a darker aggregate of somewhat larger grain size. Hence this surface appears as having relatively dark stones protruding from a matrix of a more light colour, and $\bar{q}$ is expected to be large at small distances, but decreasing with distance. This is the type of variation shown by the measured SL, which again is presumably well accounted for by the variation of $\bar{q}$.

Sample No. 617 is a surface treatment with large chippings of a uniform size (12 to 16 mm) and lightness. For this surface $\bar{q}$ should be expected to be roughly independent of the distance and thus cannot account for the measured variation of SL.

The initial decrease in SL at short distances for this sample is considered to represent a decrease in the factor of texture, $f_{\text{texture}}$.

For this surface the SL is very high at short distances considering the moderate lightness of the chippings (light granite). At 15 m the SL of 20.4 mcd/m²/lux is matched only by sample No. 63 with its very light matrix.

The value of $f_{\text{texture}}$ is, therefore, assumed to be high for sample No. 617 at short distances. This assumption is reasonable, as at short distances the strongly inclined sides of the coarse chippings can be illuminated.

At larger distances the illumination of the sides of the chippings must decrease strongly, $f_{\text{texture}}$ must decrease to values typical of less coarse surfaces, and
SL must take a value typical of a surface with aggregates of moderate lightness. This last-mentioned aspect is verified by the SL-value at 50 m of 14.9 mcd/m²/lux, which is surpassed by most of the other samples.

Hence the initial decrease in SL for sample No. 617 for distances up to 50 m is explained by a variation of the factor of texture. This variation is, on the other hand, explained by the "uniformity" of the surface, consisting of densely packed chippings of one size only.

The following variation in SL, a decrease at 75 m followed by an increase at 100 m, is ascribed to measuring uncertainty. In this very coarse surface the measuring field is strongly elongated and cannot be contained on the sample at either of the above-mentioned distances.

The other seven samples all show an SL, which is roughly independent of the distance.

It is concluded, therefore, in agreement with the model considerations that for most road surfaces neither $\bar{q}$ nor $f_{\text{texture}}$ will vary significantly with the distance (with $c$). Some surfaces do, however, show variations that relate to the appearance of the surface.

5.4.3 Influence of transverse distance of the headlight

As discussed in section B.4 a transverse displacement of the headlight to a supplemental azimuthal angle, $\beta'$ differing from zero is expected to cause a reduction in SL. The magnitude of this reduction is further expected to be determined by two parameters, $p_1$ and $p_2$:

$$p_1 = \frac{\beta'}{\alpha - \varepsilon} \cdot \frac{D_t}{H_0 - H_h}$$

$$p_2 = \alpha - \varepsilon \cdot \frac{H_0 - H_h}{D}$$
In order to test these expectations, fig. 5.6 shows the measured deviations as a function of D for $H_0 = 1.2\, \text{m}$ and for $D_t = 0.5\, \text{m}$, $1\, \text{m}$ and $1.5\, \text{m}$. In this diagram, $p_1$ changes with $D_t$ only and has the values of $0.91$, $1.82$ and $2.73$ respectively. The other parameter, $p_2$ is independent of $D_t$, but varies with $D$.

It is seen that the deviations follow curves for the various $D_t$ that are of similar shapes, but of different magnitudes. This is taken as a confirmation of the assumption of independent actions of $p_1$ and $p_2$ through factors; i.e. the reduction is given as the product $F_1 \cdot F_2$, where $F_1$ is a function of $p_1$ only and $F_2$ is a function only of $p_2$.

In this sense $F_2(p_2)$ determines the shape of the curves, while $F_1(p_1)$ determines the magnitude of the reductions in $SL$.

When taking $F_1$ to be almost at its maximum at $p_1 = 2.73$, $F_1$ is seen to be larger than half its maximum at $p_1 = 1.82$, but less than half its maximum at $p_1 = 0.91$. This is also in agreement with the model considerations.

The shape of the curves is further in agreement with the model considerations. $F_2$ is small, when $p_2$ is large, and then increases, when $p_2$ decreases below a critical value, $p'_2$. This critical value seems to be appr. $0.01$ radians.

A further illustration of the influence of $p_2$ is given in fig. 5.7 which shows the reduction in $SL$ as a function of $D$ for $D_t = 1\, \text{m}$ and $H_0 = 1\, \text{m}$, $1.2\, \text{m}$ and $1.5\, \text{m}$. Assuming a $p'_2$ of appr. $0.01$ radians, the decrease in $SL$ should remain small at $D$ up to appr. $30\, \text{m}$, $50\, \text{m}$ and $75\, \text{m}$ respectively. This actually is observed.
Figure 5.6 Deviations in SL for H = 1.2 m and Dₜ = 0.5 m, 1 m and 1.5 m, as compared to SL for Dₜ = 0.

Ændringer i SL for H₀ = 1,2 m og Dₜ = 0,5 m, 1 m og 1,5 m i forhold til "SL for Dₜ = 0."
Figure 5.7 Deviations in SL for $H_o = 1$ m, 1.2 m and 1.5 m at $D_t = 1$ m, as compared to SL for $D_t = 0$.

Endringer i SL for $H_o = 1$ m, 1.2 m og 1.5 m ved $D_t = 1$ m, i forhold til SL for $D_t = 0$. 
It is to be explained in connection with fig. 5.7 that not only $p_2$, but also $p_1$ changes with $H_0$, $p_1$ having the values of 2.86, 1.82 and 1.18. For this reason the decrease in SL in addition to setting in at shorter distances is also stronger, when $H_0$ is small.

The actual reductions of SL for the various positions in the reflection table are shown in table 5.5 as averages for the 10 samples. The values of $p_1$ and $p_2$ are given in tables 5.6 and 5.7 respectively.

On the basis of a comparison of the above-mentioned tables, it is suggested that $F_2$ is given by:

$$F_2 = \begin{cases} 0.1 & \text{for } p_2 > 0.01 \text{ radians} \\ (0.1 + 0.5(1 - \frac{p_2}{0.01})) & \text{for } p_2 < 0.01 \text{ radians} \end{cases}$$

This allows a computation of $F_2$ for each of the positions in the reflection table, and hence $F_1$ can be computed as the ratio of the reduction of SL to the computed value of $F_2$. In this way $F_1$ is determined for all positions in the reflection table (for which the $p_1$ values are also known).

The results of these calculations are shown in the $F_1$-$p_1$ diagram of fig. 5.8. The scatter in this diagram is due partly to measuring uncertainty, and partly to an even more complex variation of the reduction in SL with the measuring angles.

The model considerations are, therefore, not precise in accounting for the variation of the factor $f_{\text{visible}}$, which seems to be quite complex.
Table 5.6  Average reductions in SL, as compared to SL for $\beta' = 0^\circ$.

Gennemsnitlige reduktioner af SL i forhold til SL for $\beta' = 0^\circ$. 

| $\epsilon$ | $\alpha$ | $\beta'$ | $0.57^\circ$ | $0.69^\circ$ | $0.76^\circ$ | $0.92^\circ$ | $1.15^\circ$ | $1.37^\circ$ | $1.72^\circ$ | $1.91^\circ$ | $2.29^\circ$ | $2.86^\circ$ | $3.81^\circ$ | $4.57^\circ$ | $5.71^\circ$ | $6.84^\circ$ | $8.53^\circ$ |
|-----------|----------|----------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
| 0.37°     | 0°       | 0°       | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            |
| 1°        | 31.7%    | 24.8%    |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 0.50°     | 0°       | 0°       | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            |
| 1°        | 35.4%    | 24.0%    | 6.6%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 0.74°     | 0°       | 0°       | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            |
| 1°        | 22.9%    | 6.3%     | 3.1%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 3.5°      | 12.1%    | 8.2%     | 5.2%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 1.24°     | 0°       | 0°       | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            |
| 1°        | 4.3%     | 4.9%     | 1.2%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 2°        | 6.5%     | 3.2%     | 3.7%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 3.5°      | 11.3%    | 7.5%     | 3.7%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 2.48°     | 0°       | 0°       | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            |
| 2°        | 2.7%     | 2.5%     | 0%            |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 5°        | 12.3%    | 9.1%     | 5.8%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 3.72°     | 0°       | 0°       | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            | 0°            |
| 2°        | 2.1%     | 0%       | 0%            |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |
| 5°        | 11.1%    | 6.9%     | 6.0%          |               |               |               |               |               |               |               |               |               |               |               |               |               |               |               |


| $\varepsilon$ | $\alpha$ | $0.57^\circ$ | $0.69^\circ$ | $0.76^\circ$ | $0.92^\circ$ | $1.15^\circ$ | $1.37^\circ$ | $1.72^\circ$ | $1.91^\circ$ | $2.29^\circ$ | $2.86^\circ$ | $3.81^\circ$ | $4.57^\circ$ | $5.71^\circ$ | $6.84^\circ$ | $8.53^\circ$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $0.37^\circ$ | $1^\circ$ | 0 | 0 | 0 | | | | | | | | | | | | |
| $0.50^\circ$ | $1^\circ$ | 0 | 3.12 | 2.56 | | | | | | | | | | | | |
| $0.74^\circ$ | $1^\circ$ | 0 | 2.44 | 1.59 | 1.02 | | | | | | | | | | | |
| | $2^\circ$ | 0 | 4.88 | 3.17 | 2.04 | | | | | | | | | | | |
| $1.24^\circ$ | $1^\circ$ | 2.98 | 1.90 | 1.23 | | | | | | | | | | | | |
| | $2^\circ$ | 0 | 5.22 | 3.33 | 2.16 | | | | | | | | | | | |
| | $3.5^\circ$ | 1.49 | 0.95 | 0.62 | | | | | | | | | | | | |
| $2.48^\circ$ | $2^\circ$ | 0 | 1.50 | 0.96 | 0.62 | | | | | | | | | | | |
| | $5^\circ$ | 0 | 3.76 | 2.39 | 1.55 | | | | | | | | | | | |
| $3.72^\circ$ | $2^\circ$ | 0 | 0 | 0 | | | | | | | | | | | | |
| | $5^\circ$ | 0 | 1.01 | 0.64 | 0.42 | | | | | | | | | | | |

Table 5.7 Values of $p_1 = \beta'/(\alpha - \varepsilon)$

Værdierne af $p_1 = \beta'/(\alpha - \varepsilon)$
Table 5.8 Values of $p_2 = \alpha - \epsilon$ (radians)

Wærdierne af $p_2 = \alpha - \epsilon$ (radianer)
However, the function indicated in fig. 5.8 does account for the major part of the variations. This function is:

\[
F_1 = \begin{cases} 
\frac{1}{3} p_1 & \text{for } p_1 \leq 3 \\
1 & \text{for } p_1 > 3 
\end{cases}
\]

The reductions in SL are then approximated by:

\[F_1 \cdot F_2\]

where \(F_1\) and \(F_2\) are the functions of \(p_1\) and \(p_2\) respectively, as given above.

A comparison between computed and measured reductions in SL is given in fig. 5.9.

5.5 Moist condition

In the moist condition the stones in the surface are covered by a water film, and for some surfaces, water "pools" can form in the bottom of the texture.

These water films and surfaces create a strong specular reflection, which is important in some illumination situations. For the reflection in the illumination of the driver's own headlight, specular reflection is, however, not important. Only a few illuminated facets will have the almost vertical orientation required for mirror reflection, and in this orientation the reflectance of a water film is small.

The important aspect of the moisture is, therefore, a dark-colouring of the stones, and the further dark-colouring of such lower parts of the texture covered by water.
Figure 5.8 Average values of $F_1$ determined by means of the average reductions of SL given in table 5.5 and plotted against $p_1 = \beta'/(\alpha-\epsilon)$.

Gennemsnitlige værdier af $F_1$ beregnet på baggrund af de gennemsnitlige reduktioner af SL, som er givet i tabel 5.5, og afsat i forhold til $p_1 = \beta'/(\alpha-\epsilon)$. 
MEASURED REDUCTIONS OF SL
1-SL/SL(β' = 0°)

Figure 5.9 Comparison between measured and computed reductions of SL.

The influence of the moisture can thus be expected to be a reduction of the average luminance coefficient of illuminated facets, ̃q and a consequent reduction of SL-values. There is no reason to expect a significant change in the influence of the geometry.

The above-mentioned expectations have been partly confirmed in previous measurements. In the investigation reported in Mørkertrafik Report No. 2, the effect of
moisture was found to be a reduction of SL by a factor of 2 to 7.

A further expectation, also partly confirmed in previous measurements, is that the degree of moisture is not important over a wide range. This was tested and confirmed for the 10 road samples prior to the main measurements. For this reason the very simple wetting procedure described in chapter 4 was used.

The diagrams of fig. 5.10 to 5.13 are set up in order to test the assumption that for a certain road sample any SL-value for the humid condition is approximately a certain fraction of the corresponding SL-value for the dry condition. The fraction is characteristic of the road surface, but can vary among road surfaces.

If this assumption is verified, the influence of the geometry, as established in section 5.4 for the dry condition, can be considered to be valid also for the humid condition.

In the log-log diagrams giving SL(humid) in relation to SL(dry) for identical geometries, the assumption means that all points are to lie close to a line of the slope one decade per decade (45° in the diagrams). Lines of this slope are, therefore, drawn through one of the points. The selected point is for the geometry of (ε = 0.74°, α = 1.37°, β' = 0°).

It is seen from the diagrams that the points do fit to some extent around the lines. Deviations from this fit are partly due to measuring uncertainty for the dry and in particular for the humid condition.

Measuring uncertainties are clearly largest for the humid condition for at least two reasons. First, variations in the degree of humidity do cause an increase in the uncertainty. Next, the values are
smaller and closer to the lower range of the equipment. For sample No. 90, 4 very small values (0.1 to 0.7 mcd/m²/lux) have been deleted from the diagram, as they were clearly very uncertain.

For some of the samples, e.g. No. 609, a better fit could obviously be obtained to a line of a steeper slope. This could be taken to mean that the influence of the geometry is somewhat different in the humid condition.

A closer study of the influence of the geometry by means of diagrams as for the dry condition (the diagrams are not shown) revealed the following.

Some of the samples show a tendency of SL (humid) increasing somewhat with the distance. The reason for this is probably a relatively stronger reduction of SL at short distances, where the very dark, flooded lower parts of the texture are illuminated.

Another difference from the dry condition seems to be a stronger influence of the observer eye height, being in fact in better agreement to the model considerations for the humid condition. The reason for this is again presumably that facets of a low inclination are covered by water.
Figure 5.10 SL(humid) in relation to SL(dry) for samples Nos. 63, 601 and 609.

SL(fugtig) i relation til SL(tør) for prøver nr. 63, 601 og 609.
Figure 5.11 SL(humid) in relation to SL(dry) for samples Nos. 460, 617 and 87.

SL(fugtig) i relation til SL(tør) for prøver nr. 460, 617 og 87.
Figure 5.12 SL(humid) in relation to SL(dry) for samples Nos. 90 and 176.

SL(fugtig) i relation til SL(tør) for prøver nr. 90 og 176.
Fig. 5.13 SL(humid) in relation to SL(dry) for samples Nos. 177 and 182.

SL(fugtig) i relation til SL(tør) for prøver nr. 177 og 182.
6. APPLICATION
By Kai Sørensen, LTL

6.1 Introduction to a description system
A necessary basis for applications of reflection properties of road surfaces is that the reflection properties can be described (or classified) in a way that permits simple measurements of parameters, which describe the reflection properties to a sufficient accuracy.

For the illumination by street lighting the choice of descriptions and classifications has involved a large amount of research that is still carried on.

In the case of illumination by the drivers own headlights, as considered in this report, it seems possible to introduce a rather simple description.

The parameter of a simple description can be the SL-value for a selected standard geometry. The SL-value for the standard geometry can be distinguished by a mark, SL'.

The description of the reflection properties consists of course of an estimation of the SL for other geometries than the standard geometry. This estimation can be carried out by means of the model for the influence of the geometry, as introduced in Appendix B and as investigated and completed in chapter 5.

A further convenient feature is that the same model applies to both the dry and the humid condition. A description of the reflection properties for both conditions involves, therefore, only the specific luminances for the two conditions, SL'(dry) and SL'(humid).

The SL'(humid) can even represent a wide range of humid conditions, due to the relative insensitivity
of SL to the actual degree of humidity of the surface.

This simple description is defined, when the standard geometry is selected, and when also the formulas for the transformation to other geometries are given.

Some considerations concerning the choice of a standard geometry are given in section 6.2. A standard geometry is not actually proposed yet, as it should be attempted to select a standard geometry, which is applicable to road markings as well as road surfaces.

Section 6.3 gives, on the other hand, a proposal for a set of formulas, which need not be common to road surfaces and road markings.

6.2 Considerations concerning a standard measuring geometry

It is natural for reasons of symmetry to select a standard measuring geometry, where the azimuthal angle, $\beta$ is $180^\circ$ ($\beta' = 0^\circ$).

The choice of the observation angle, $\alpha$ is best done in relation to the illumination angle, $\varepsilon$, assuming a typical geometry of the vehicle.

The critical step in the choice of the standard measuring geometry, therefore, concerns the illumination angle, $\varepsilon$. As headlight mounting heights presumably vary little, the choice of $\varepsilon$ can be considered to be a choice of a simulated distance on the road.

One consideration concerning the simulated distance on the road is its consequences for the measuring equipment. Without going into detail it can be stated that large measuring distances are much more demanding than small distances.

This is undoubtedly the reason why existing portable equipments, with a few exceptions, use geometries cor-
responding to very short distances of appr. 10 m on the road. One such geometry of \( \varepsilon = 3.5^\circ, \alpha = 5^\circ \) is even given in DIN Standard No. 67520, part 1-3 (draft) for the measurement of road markings.

Two other instruments use geometries corresponding to longer distances of appr. 30 m and 50 m, see VTI Report No. 188A concerning these two instruments and an instrument built according to the DIN-standard.

It is interesting to see, if the shortest distance of appr. 10 m permits a description of a sufficient accuracy, or whether the longer distances are required and lead to worthwhile improvements.

In the analysis the three distances of 10 m, 30 m and 50 m are represented by the positions of the reflection table of \( (\varepsilon = 3.72^\circ, \alpha = 5.71^\circ) \), \( (\varepsilon = 1.24^\circ, \alpha = 2.29^\circ) \) and \( (\varepsilon = 0.74^\circ, \alpha = 1.37^\circ) \) respectively. The first-mentioned geometry corresponds to an observer eye height, \( H_O \) of 1 m, giving the best agreement to the DIN-standard, while the other two geometries corresponds to \( H_O = 1.2 \) m.

The analysis is further based on the implication of the model considerations that reflection tables for different road surfaces, and even for dry and humid conditions, are identical except for the scale of the SL-values of the tables.

A measure of the potential accuracy of a certain position to be used for the standard geometry is obtained in the following manner.

Each of the tables for the 10 road samples are rescaled, so that the value at the position in question is unity. At all other positions the values will vary from table to table. This variation is expressed as the RMS percentage variation around the average value.
The result is a table in the format of the reflection table, which position for position expresses a percentage uncertainty.

These uncertainties include measuring uncertainties, which will enter any analysis. The uncertainties include further deviations from the above-mentioned implication of the model considerations. It is actually such deviations that make some geometries preferable to other geometries for the use as the standard geometry. If the model considerations had led to a very accurate picture of the SL-values of real surfaces, all geometries would do equally well as the standard geometry.

The model considerations not only imply the above-mentioned similarity of reflection tables, but give also the variation of the SL-value from position to position in the table.

The complete account of the reflection table is a further approximation to the SL-values of real surfaces, which again increases the uncertainty of the complete description. This increase in uncertainty is considered in section 6.3, but does not enter the analysis of this section, which, therefore, gives an improved judgement of the consequences of the choice of the standard geometry.

The uncertainty tables for the 10 m, 30 m and 50 m geometry are shown in tables 6.1 to 6.3 respectively, as computed for the reflection tables for the dry condition.

Assuming a maximum permissible uncertainty of 15 % for the dry condition, it is seen from table 6.1 that the 10 m geometry covers geometries with a satisfactory accuracy in a range up to 30 m only. The 30 m geometry similarly covers a range from 10 m to 50 m, while the 50 m geometry covers a range of geometries from 30 m to 75 m.
Table 6.1 Variations (percent) among the SL-values of the ten road samples in the dry condition after a rescaling of the SL for the 10 m geometry ($\varepsilon = 3.72^\circ$, $\alpha = 5.71^\circ$) to unity.

Variationer (procent) blandt SL-værdierne for de ti vejprøver i tør tilstand efter en omskalering, så SL for 10 m geometrien ($\varepsilon = 3.72^\circ$, $\alpha = 5.71^\circ$) er én.
Table 6.2 Variations (percent) among the SL-values of the ten road samples in the dry condition after a rescaling of the SL for the 30 m geometry ($\varepsilon = 1.24^\circ$, $\alpha = 2.29^\circ$) to unity.

Variations (procent) blandt SL-værdierne for de ti vejprøvgr i tør tilstand efter en omskalering, så SL for 30 m geometrien ($\varepsilon = 1,24^\circ$, $\alpha = 2,29^\circ$) er én.
Table 6.3 Variations (percent) among the SL-values of the ten road samples in the dry condition after a rescaling of the SL for the 50 m geometry ($\varepsilon = 0.74^\circ$, $\alpha = 1.37^\circ$) to unity.

Variationer (procent) blandt SL-værdierne for de ti vejprøver i tør tilstand efter en omskalering, så SL for 50 m geometrien ($\varepsilon = 0,74^\circ$, $\alpha = 1,34^\circ$) er én.
Similar conclusions are reached for the humid condition assuming a maximum permissible uncertainty of 25 % (tables not shown).

It is to be pointed out that a significant part of these uncertainties are due to the rather large variations of SL with the distance, as shown by the samples No.s 460, 63 and 617 for the reasons given in chapter 5.

When these three samples are excluded from the calculation of the uncertainties, the above-mentioned ranges of distances are covered to an uncertainty of only 10 % for the dry condition, and 20 % for the humid condition (tables not shown).

In interpreting these findings emphasis should be put on the accuracy of description for the larger distances. This emphasis does not necessarily mean that short distances are irrelevant to the drivers visual needs. The meaning is rather that the longer distances are certainly as important as the shorter ones, and they are simultaneously more critical, as the illumination is much smaller.

In this sense the 50 m geometry is clearly the best, the 30 m geometry is perhaps acceptable, and the 10 m geometry is unacceptable.

6.3 Transformation to other geometries

The SL-value for the standard geometry, SL', is assumed to be determined in a measurement. The SL for other geometries can then according to Appendix B and chapter 5 be estimated by:

\[ SL(\varepsilon, \alpha, \beta') = \frac{f_{\text{geometry}}}{f_{\text{geometry}}} \cdot f_{\text{visible}} \cdot SL' \]

where \( f_{\text{geometry}} \) is the factor of geometry for the standard geometry.
f_{geometry} is the factor of geometry for the geometry considered.

and \( f_{visible} \) is the factor of visible, illuminated facets of the geometry considered.

In setting up this expression for the estimation of SL it has been assumed that \( f_{visible} \) is unity for the standard geometry (\( \beta' = 0^\circ \) in this geometry). It is further assumed, the \( \tilde{q} \) and \( f_{texture} \) do not change from one geometry to another.

The factor, \( f_{geometry} \) has a fixed value, which has to be computed only once for a selected standard geometry.

The factor \( f_{geometry} \) is given by:

\[
f_{geometry} = \frac{\sin \epsilon}{\sin \alpha}
\]

where \( \epsilon \) and \( \alpha \) are the angles of illumination and observation for the geometry considered.

The factor, \( f_{visible} \) can according to chapter 5 be estimated by:

\[
f_{visible} = 1 - F_1(p_1) \cdot F_2(p_2)
\]

where \( F_1 = \begin{cases} \frac{1}{3} p_1 & \text{for } p_1 \leq 3 \\ 1 & \text{for } p_1 > 3 \end{cases} \)

\[
p_1 = \frac{\beta'}{\alpha - \epsilon}
\]

\[
F_2 = \begin{cases} 0.1 & \text{for } p_2 \geq 0.01 \\ 0.1 + 0.5 \left(1 - \frac{p_2}{0.01}\right) & \text{for } p_2 < 0.01 \end{cases}
\]

\[
p_2 = \alpha - \epsilon \text{ (radians)}
\]
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Table 6.4 Variations (percent) of the measured SL-values of the ten road samples in the dry condition from the values predicted by the transformation from the 50 m geometry ($\varepsilon = 0.74^\circ, \alpha = 1.37^\circ$).

Variationer (procent) af de målte SL-værdier for de ti vejprøver i tørr tilstand i forhold til de værdier, som forudsiges ved transformation fra 50 m geometrien ($\varepsilon = 0.74^\circ, \alpha = 1.37^\circ$).
The accuracy of the estimation can possibly be improved by taking variations of $\tilde{q}$ and $f_{\text{texture}}$ into account for such surfaces, where these factors are expected to vary in a certain fashion.

The expression for $f_{\text{geometry}}$ is one of definition and cannot be modified. The expression for $f_{\text{visible}}$ has been derived by a fit to the measuring data and can possibly be improved, if more data become available.

When using this method of estimation, and assuming the 50 m standard geometry ($\varepsilon = 0.74^\circ$, $\alpha = 1.37^\circ$), the RMS uncertainties for the 10 road samples can be computed for all positions in the reflection table. The results of such computations are given in table 6.4 for the dry condition.

A comparison of table 6.4 to table 6.3 shows some increase in the uncertainties, which is due to the more detailed assumptions given above. The increase in uncertainties is, however, not a serious one.

**Example of transformation**

For a geometry of $(\varepsilon = 0.74^\circ, \alpha = 1.37^\circ, \beta' = 0^\circ)$ $SL'$ has been measured for a certain road surface to 20 mcd/m²/lux. The factor of geometry, $f'_{\text{geometry}}$ is $0.74^\circ/1.37^\circ = 0.54$.

For this road surface is desired an estimation of the $SL$ for both headlights at a distance $D = D_h = D_o = 100$ m for a sportscar with a headlight mounting height, $H_h$ of 0.70 m and an observer eye height, $H_o$ of 1 m.

The factor of geometry, $f_{\text{geometry}}$ for this vehicle is $0.70$ m/$1$ m = 0.7. Hence a correction factor of $0.70/0.54 = 1.30$ applies for this vehicle.
For the headlight in the steering side the transverse displacement, \( D_t \) is approximately 0, and hence \( f_{\text{visible}} = 1 \) and:

\[
\text{SL(headlight in steering side)} = 1.30 \times 20 \text{ mcd/m}^2/\text{lux} = 26 \text{ mcd/m}^2/\text{lux}.
\]

For the other headlight \( D_t = 1 \) m and a smaller value of \( f_{\text{visible}} \) applies.

The parameter, \( p_1 \) is computed to \( D_t / (H_0 - H_h) = 3.33 \), which is higher than 3. Therefore, the values of \( 1 \) is taken for \( F_1 \).

The parameter, \( p_2 \) is \( (H_0 - H_h) / D = 0.003 \). This value is smaller than 0.01 and, therefore, \( F_2 \) is calculated by:

\[
F_2 = 0.1 + 0.5(1 - \frac{p_2}{0.01}) = 0.1 + 0.5(1 - 0.3) = 0.45
\]

This gives an \( f_{\text{visible}} \) of \( 1 - F_1 \cdot F_2 = 1 - 0.45 = 0.55 \) and:

\[
\text{SL(other headlight)} = 1.30 \times 0.55 \times 20 \text{ mcd/m}^2/\text{lux} = 14 \text{ mcd/m}^2/\text{lux}.
\]
SUMMARY

By Kai Sørensen, LTL

A measuring equipment at the National Road & Traffic Research Institute (VTI), Linköping, Sweden has previously been used for the study of reflection properties of road surfaces and road markings in vehicle headlight illumination. The equipment allows the setting of the angles of illumination, $\varepsilon$ and of observation, $\alpha$.

This equipment has been fitted with a mirror arrangement, which allows also the third angle of the geometry, the azimuthal angle, $\beta$ to be set. The equipment has further been fitted with a displaceable sampleholder used for the scanning of the measuring field, and a semiautomatic data-registration using paper-tape. The equipment is described in chapter 4.

This equipment is intended for a number of studies of road surfaces and road markings with the aim of selecting standard measuring geometries for in situ measurements. Plans for these studies are found in Mörkertrafik Report No. 3.

This study concerns the specific luminance, $SL$ of road surfaces in the illumination of the drivers own headlights. Among existing road samples were selected a number of ten. Some of these are typical of Swedish and Danish road surfaces, while others were included for the reason that they were suspected to show special features of reflection properties.

The road samples are introduced in chapter 2, while definitions and notations are given in chapter 3.

The measuring geometries were selected with reference to geometrical situations in car driving.
Situations of simulated distances of 10 m to 100 m, observer eye height of 1 m to 1.5 m and transverse displacements between observer and headlight up to 1.5 m are considered, when assuming a headlight mounting height of 0.65 m.

The measuring geometries are, however, specified in terms of the measuring angles and are given by a reflection table of 51 positions. The reflection tables for the ten samples in dry and a humid condition are given in Appendix A.

In order to facilitate the discussion of the measuring data, and to give a general understanding of the reflection, model considerations of the reflection are discussed in Appendix B.

The model considerations indicate that SL can be represented as the product of 4 factors:

\[ SL = q \cdot f_{\text{geometry}} \cdot f_{\text{texture}} \cdot f_{\text{visible}} \]

where \( q \) is the average luminance coefficient of illuminated facets and represents the lightness of the aggregates in the surface

\( f_{\text{geometry}} \) equals \( \text{sinc}/\text{sina} \) and accounts for the major part of the influence of the angles \( \varepsilon \) and \( \alpha \)

\( f_{\text{texture}} \) is a measure of the average inclination of the illuminated facets

and \( f_{\text{visible}} \) is the fraction of illuminated facets that are also visible. This factor accounts for the loss in SL, when \( \beta \) differs from \( 180^\circ \).

The model considerations further imply that \( q \) and \( f_{\text{texture}} \) will often be approximately independent of
the geometry, and that \( f_{\text{visible}} \) is to some approximation the same function of the angles for all surfaces.

This indicates that SL will approximately be the same function of the angles for most road surfaces, and that the scale of this function is given by the lightness of the aggregates (\( \bar{q} \)) and the texture \( (f_{\text{texture}}) \).

The measurements discussed in chapter 5 confirm the model considerations for the dry condition with the remark that those samples for which special features were expected, do show such features.

Thus two samples having light-coloured facets mainly in respectively the upper and lower parts of the texture do show variations in \( \bar{q} \) with the angles. Another sample, a surface treatment with chippings of a uniform size, shows a very high \( f_{\text{texture}} \), at large illumination angles, decreasing to a normal values at smaller illumination angles.

The function, \( f_{\text{visible}} \) is estimated empirically from the measuring data.

For the humid condition is established that the SL's are a fraction of the SL's for the dry condition. This fraction varies from surface to surface, but is approximately independent of the geometry. Thus the model considerations are indirectly confirmed for the humid condition also.

The reduction in SL for the humid condition is ascribed essentially to a reduction of \( \bar{q} \), which is due to the dark-colouring of the humid aggregates. Some slight changes in the influence of the geometry for the humid condition are explained by the additional dark-colouring of the more humid, lower parts of the surface texture.
It is further stated, as it has been observed at earlier occasions that SL does not vary strongly with the actual degree of humidity. For this reason a simple wetting procedure has been used.

In chapter 6 it is concluded that the findings are favourable for application purposes. A description can be based on the SL-value of a standard measuring geometry, with the estimation of SL-values for other geometries carried out by means of the formulas derived in the model considerations and supplemented by the measuring data.

The observed deviations from the formulas do, on the other hand, necessitate a proper choice of the standard geometry. It is shown that when emphasis is put to the accuracy of the description for geometries of middle and long simulated distances, a geometry corresponding to a simulated distance of 50 m is better than geometries corresponding to shorter distances. Geometries corresponding to appr. 10 m, as found in some commercially available instruments, are very poor in this respect.

The accuracy of the complete description system, as based on an assumed standard geometry of 50 m, is found to be acceptable.

However, a proposal for a standard geometry is not included, as a standard geometry should, if possible, apply also to road markings. A study of road markings similar to this one is, therefore, being undertaken.
8. **SAMMENFATNING**

Af A.O. Bohn, for Statens Vejlaboratorium

Veje med faste belysningsanlæg kan lysteknisk set bedst karakteriseres ved luminansen i candela pr. m² af de af trafikanten betragtede områder af vejoverfladen. Luminansen kan siges at være et mål for, hvor lys vejen ser ud for trafikanten. For veje, der oplyses udelukkende af bilistens egne lygter, duer luminansen ikke - den ville være afhængig af bilens belysningsanlægs effektivitet. Mest formålstjenligt er det, at interessere sig for den såkaldte specifikke luminans, SL som i diagrammerne måles i millicandela pr. m² pr. lux. SL blev tidligere kaldt retrorefleksionen; den angiver, hvor stor en del af trafikantens eget lys, der rammer det betragtede sted på vejen, som reflekteres i retning af trafikantens øjne. Den eksakte definition findes i kapitel 3.

LTL (Lysteknisk Laboratorium) har støttet af Vejdirektoratet været med i et nordisk samarbejde om måling af SL af vejprøver og vejafmærkninger.

Det i tabel 2.1 viste udvalg af typiske (og lysteknisk interessante) skandinaviske vejprøver er blevet undersøgt på VTI (Statens Väg- og Trafikinstitut) i Linköping på en derværende velegnet stationær målepstilling (fig. 4.1).

I samarbejde med LTL blev målepstillingen forbedret; blandt andet blev den ændret, så at man ikke alene kunne måle SL for situationen, hvor jagttageren befandt sig lodret over lygten ("motorcykelsituationen"), men også, når der var en vis afstand til siden, som tilfældet er ved automobilkørsel.

Betragtes figur 3.1, betød ændringen, at man nu også så kunne ændre den for sideforskydningen, $D_t$.
afgørende vinkel $\beta'$- hidtil havde man kun kunnet ændre belysningsvinklen $\varepsilon$ og observationsvinklen $\alpha$. Observationsafstanden $D_0$ til det betrægtede punkt $P$ bestemmer, som det ses af figuren, disse to vinkler i forbindelse med henholdsvis lygtehøjden $H_h$ og observationshøjden $H_o$. Ved målingerne benyttes et mod punktet $P$ rettet luminansmeter, placeret i observationspunktet. En situation på vejen, hvor observatøren betragter et område af vejen, der f.eks. er 75 m borte, kan simuleres ved laboratorieopstillingen trods de relativt små dimensioner ved at vælge samme geometri, d.v.s. samme værdier af $\varepsilon$, $\alpha$ og $\beta'$. Det var muligt med et spejlarrangement direkte at indstille 5 forskellige, faste værdier af $\beta'$. SL for andre værdier kunne findes ved interpolation.

På fig. 5.1 og i tabel 5.1 ses hvilke afstande, $D$ på vejen (fra 10-100 m), hvilke øjenhøjder $H_o$ (fra 1-1.5 m) og hvilken lygtehøjde $H_h$ (0,65 m) man ønskede at simulere ved valget af vinkelsættene, og hvilke værdier af $\varepsilon$ og $\alpha$ der svarer hertil. Fig. 5.2 viser, hvordan man finder de $\beta'$ værdier, der svarer til de ønskede lygtesideforskydninger $D_t$. De tilstræbte værdier for $D_t$ (fra 0-1,5 m) fremgår af tabel 5.2, hvor man ser, hvilke værdier $\beta'$ skal have for de valgte værdier for $D$ og $D_t$. I tabel 5.4 er der afkrydset hvilke vinkelkombinationer, der valgtes til målingerne - at de afkrydsede felter grupperer sig om en diagonal, betyder blot, at man, når man vælger en række belysningsvinkler $\varepsilon$, kun har interesse i at måle med de observationsvinkler $\alpha$, der svarer til, at man ser på det belyste sted på vejen.

Måleudstyret var udbygget med en semiautomatisk dataregistrering på hulbånd. Tabel 5.5. viser, som et eksempel, en EDB-udskrevet refleksionstabel for prøve 601, en 0/12 mm asfaltbeton med 20 % tilslag af calcineret flint. Refleksionstabeller for samtlige vej-
prøver i våd og tør tilstand findes i Appendix A. På figur 5.3 ses en grafisk afbildning af tabel-lens tal - her er der ikke anført vinklerne, men de hertil svarende kombinationer af observations-afstande D, observationshøjder H₀, lygtehøjde Hₕ og lygtesideforskydninger Dₜ. Der gøres her opmærksom på det hensigtsmæssige i at se bort fra visse diagrampunkter, hvor usikkerheden er stor.

Af figuren ses - hvad der fremgår endnu tydeligere af fig. 5.4, at SL er relativt større for små observationshøjder end for store. Det stemmer - også kvantitativt - med de i Appendix B anførte modelbetragtninger, hvorefter man skulle forvente, at SL var proportional med størrelsen fₛGeometry, som er forholdet mellem sinus til henholdsvis belysnings-vinklen ε og observationsvinklen α.

Modelbetragtningerne antyder, at SL kan repræsenteres af et produkt af 4 faktorer:

\[ SL = \bar{q} \cdot f_{\text{geometry}} \cdot f_{\text{texture}} \cdot f_{\text{visible}} \]

hvor \( \bar{q} \) er den gennemsnitlige luminanskoefficient af belyste facetter og dermed er et mål for lysheden af stenene i overfladen

\( f_{\text{geometry}} \) er givet ved \( \sin \varepsilon / \sin \alpha \) og redegør for hovedparten af indflydelsen af vinklerne ε og α

\( f_{\text{texture}} \) er et mål for den gennemsnitlige hældning af de belyste facetter

og \( f_{\text{visible}} \) er den brøkdel af de belyste facetter, der også er synlig. Denne faktor redegør for det fald i SL, der indtræffer, når \( \beta' \neq 0^\circ \).
Modelbetrætningerne antyder desuden, at \( \tilde{q} \) og \( f_{\text{texture}} \) med nogen tilnærmelse er den samme funktion af vinklerne for alle vejbelægninger.

Dette medfører, at SL med tilnærmelse er den samme funktion af vinklerne for de fleste vejbelægninger, og at denne funktions skalaforhold bestemmes af lys-heden af stenene i overfladen (\( \tilde{q} \)) og af tekturen (\( f_{\text{texture}} \)).

Funktionen \( f_{\text{visible}} \) bestemmes empirisk ved tilpasning til måleresultaterne.

Måleresultaterne, som diskuteres i kapitel 5, bekræfter modelbetrætningernes gyldighed for de tørre vejprøver med den bemærkning, at de prøver, for hvilke der forventedes specielle forhold, også udviser så-danne forhold.

På fig. 5.5 vises SL for samtlige prøver uden tvar-forskydning af lygten. Der er divideret med SL værdien for \( D = 50 \text{ m} \), således at samtlige kurver går gennem 50,1. Resultaterne, som er vigtige for diskussionen af, hvilken geometri man bør vælge til et transportabelt refleksionsmåleapparat, viser, at for 7 af de 10 undersøgte asfaltbelægninger var der ingen større variation i SL med afstanden. Der var 3 undtagelser fra dette: a) En belægning - nr. 460 - med 4/8 mm nedtromlede lyse sten i en mørk, finkornet grundmasse. Her var SL lille ved kort betrætningsafstand, hvor måleapparatet "så" ned på den mørke grundmasse mellem de hvide sten, mens man ved lang betrætningsafstand kun så de lyse sten. b) En belægning - nr. 63 - hvor 0/3 mm lyse sten befandt sig i en mørk grundmasse med større maksimalkornstørrelse. Her var det omvendt: SL var størst ved kort betrætningsafstand - på lang betrætningsafstand var de mørke store sten åbenbart dominerende. I disse to tilfælde er der åbenbart en stor afhængighed i \( \tilde{q} \) med
geometrien. c) En overfladebehandling - nr. 617 - med en lys granit. SL var stor for små afstande; ved større afstande var SL ikke større end for andre belægninger.

De på figur 5.6 og 5.7 og i tabel 5.5 viste reduktioner i SL med voksende sideforskydning, $D_T$, af lygten er også i overensstemmelse med modelbetraktningerne, idet faktoren $f_{\text{visible}}$ netop forklarer iagttagelsen. Det ses, at virkningen af sideforskydningen afhænger af $D$, betragtningsafstanden. Fig. 5.9 viser, hvorledes de målte reduktioner i SL i forhold til SL for sideforskydningen 0 stemmer med de beregnede, hvor man opnår reduktion ved at gange med reduktionsfaktorerne $F_1$ og $F_2$, hvor $F_1$ og $F_2$ hver kun er afhængig af de i tabellerne 5.6 og 5.7 viste vinkelafhængige størrelser $p_1$ og $p_2$. Overensstemmelsen er nogenlunde. $F_1$ skulle afhænge entydigt af $p_1$, men som vist i fig. 5.8 er der tale om ikke ubetydelige usikkerheder. Anderledes udtrykt: indenfor en vis fejlmargin kan SL for forskellige sideforskydninger findes, når SL for sideforskydningen 0 kendes.

Fugtes vejoverfladerne, reduceres SL; det skyldes, at luminanskoefficienten $f$ formindskes. Da de andre faktorer i modeludtrykket: $f_{\text{geometry}}$ og $f_{\text{texture}}$ ikke ændres, kan man ikke forvente at ændringer i geometrien, d.v.s. ændringer i vinklerne $\varepsilon$, $\alpha$ og $\beta'$ vil have større betydning. Det fremgår også af figurerne 5.10-5.13. Her er sammenhørende værdier af SL (fugtig) og SL (tør) for hver enkelt vejprøve for hver af de undersøgte geometrier afbildet i et log-log diagram. Vi ser, at punkterne nogenlunde ligger på en $45^\circ$ linie, her tegnet gennem punktet svarende til vinkelsituationen: $\varepsilon = 0,74^\circ$, $\alpha = 1,37^\circ$ og $\beta' = 0^\circ$.

I afsnit 6 diskuteres det vigtige spørgsmål, om hvilke afvigelser, man kan få, når man ved hjælp af
modelbetrægtninger prøver at beregne SL for en
vilkårlig vinkelsituation, når der foreligger en
måling SL' ved en standardgeometri. Nærliggende
er det at vælge $\beta' = 0$ (svarende til ingen side-
forskydning af billygten). Ved valget af $\varepsilon$ - og
dermed af modelbetrægtningens afstanden - må man ikke
for at lette apparatkonstruktionen vælge en stor
værdi for belysningsvinklen $\varepsilon$. I tabellerne 6.1,
6.2 og 6.3 vises de store variationer man ville få,
midlet for de 10 vejprøver ved at gange SL-tallene
med faktorer, der ville bevirke, at alle tal ved $\varepsilon$
være tilsvarende til, at de tre afstande på henholdsvis 10,
30 og 50 m var ens. Man ser, at tillades 15% af-
vigelse, vil et $\varepsilon$ valg, svarende til $D = 50$ m være
velegen til at forudsige SL ved afstande fra
30-75 m, hvilket er mere tilfredsstillende end de
to andre valg af $\varepsilon$, som giver unvendeligt dårlige
esitmater ved denne relativt store afstand, som må
være den vigtigste for brugeren.

Afsnittet slutter med en anvisning på, hvordan man
udfra modellloven for SL regner om fra en geometri
til en anden ved at multiplicere med forholdet mel-
lem $f_{\text{geometry}}$ før og nu og beregne $f_{\text{visible}}$ ud fra
den ændrede vinkelsituation ($f_{\text{visible}} = 1$ i standard-
geometrien). $\overline{\varepsilon}$ og $f_{\text{texture}}$ forudsættes ikke at ændre
sig. Der foretages en gennemregning af et eksempel,
hvor opgaven var at finde SL 100 m fra en bil, når
lygtehøjden, den indbyrdes lygteafstand og lagtage-
rens øjenhøjde er givet, og når SL' for $\varepsilon = 0,74^\circ$,
$\alpha = 1,37^\circ$ og $\beta' = 0$ er kendt. Det pointeres, at det
endnu er for tidligt at udtale, at netop disse vink-
ler er optimale med henblik på konstruktionen af et
transportabelt reflektometer - man må afvente resulta-
tet af målinger på vejstriber.

I Appendix A bringes SL tabellerne for de 10 tørre
og våde vejprøver, og i Appendix B udledes den før
omtalte modelllof $SL = \overline{\varepsilon} \cdot f_{\text{geometry}} \cdot f_{\text{texture}} \cdot f_{\text{visible}}$. 
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## APPENDIX A

### REFLECTION TABLES

By Kai Sørensen, LTL

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**tør tilstand**

**humid condition**

**fugtig tilstand**
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Table A.3 Reflection tables for sample No. 609.

Refleksionstabeller for prøve nr. 609.
Table A.4 Reflection tables for sample No. 460.

Refleksionstabeller for prøve nr. 460.
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Table A.7 Reflection tables for sample No. 90.

Refleksionstabeller for prøve nr. 90.
Table A.8 Reflection tables for sample No. 176.

Refleksionstabeller for prøve nr. 176.
Table A.9 Reflection tables for sample No. 177.

<table>
<thead>
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<th>humid condition</th>
<th>fugtig tilstand</th>
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<td>3.81 4.57 5.71 6.84 8.53</td>
<td>3.81 4.57 5.71 6.84 8.53</td>
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<tr>
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<td>2.46 3.24 4.35 5.10 6.17</td>
<td>2.46 3.24 4.35 5.10 6.17</td>
</tr>
<tr>
<td>BETA</td>
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<td>1.00 1.08 1.10 1.15 1.22</td>
<td>1.00 1.08 1.10 1.15 1.22</td>
</tr>
<tr>
<td></td>
<td>3.72 2.38 3.38 4.21 5.41</td>
<td>3.72 2.38 3.38 4.21 5.41</td>
<td>3.72 2.38 3.38 4.21 5.41</td>
</tr>
</tbody>
</table>
Table A.10 Reflection tables for sample No. 182.

Refleksionstabeller for prøve nr. 182.
APPENDIX B

A MODEL FOR THE SPECIFIC LUMINANCE OF ROAD SURFACES

By Kai Sørensen, LTL

B.1 - Introductory remarks

In section B.2 is given a general expression for the specific luminance, $SL$, of road surfaces. The only approximation in this expression is a disregarding of the interreflection in the texture of the surface.

The assumption underlying the general expression is that the surface can be divided into a large number of small, plane facets. This total group of facets is separated into subgroups, of which one contains illuminated facets, another facets that are visible, a third facets that are illuminated and also visible, and finally a subgroup of facets that are illuminated, but not visible.

The reflection properties of the facets are specified by luminance coefficients, whose values can in principle vary from facet to facet and with the geometry of illumination and observation. The orientation of a facet is given by the cosines of the angles between the normal of the plane of the facet and the directions from the facet towards the headlight and the observer. When these cosines are large, the facet is said in more loose terms to have a large inclination towards the headlight and the observer (towards the vehicle).

In the following sections B.3 to B.6 are introduced a number of modifications to the expression for $SL$. These modifications lead to an expression for $SL$ consisting of four factors:
an average luminance coefficient of facets, \( \bar{\varphi} \)
a factor of geometry, \( f_{\text{geometry}} \)
a factor of texture, \( f_{\text{texture}} \)
a factor of visible, illuminated facets, \( f_{\text{visible}} \)

The modifications are in themselves accurate, but useful only when the factors are interpreted in the following senses, which at the same time introduces approximations.

The average luminance coefficient reflects the lightness of the stone material in the surface and has a value of 0.01 to 0.3 say. The other factors all have values between zero and unity.

The factor of geometry is the ratio between the angles of illumination and observation. This factor reflects the major part of the influence of those angles on the SL-value.

The factor of texture is a measure of how large a part of the incident luminous flux that falls on facets of a large inclination. This factor has a value, which is a substantial fraction of unity.

The factor of visible, illuminated facets tells essentially, how large a fraction of the illuminated facets that are visible. This factor takes a value below unity, when the angle of observation is lower than the angle of illumination, or more interesting, when the supplemental azimuthal angle, \( \beta' \) differs from zero.

For all these factors there is in the relevant section a discussion of how the value relates to the geometry of illumination and observation and to the properties of the surface. Concerning the factor,
it is necessary to introduce further natural assumptions of the texture of the road surface in order to derive the principal dependence on the angles.

The above-mentioned discussion is based to some extent on the outcome of measurements. In particular the modifications of the general expression for SL are based on an observed influence of the angles and on the rather high value of SL and thereby of texture.

Otherwise the discussion is carried out on a general, or speculative basis, with the aim of giving a background for the understanding of road surface reflection properties in vehicle headlight illumination, and a background for an interpretation of the measurements.

This appendix has the further aim of showing that the characteristics of SL-variations with the geometry are not coincidences of some road surfaces, but rather are caused by the special geometry of illumination and observation.

B.2 - General expression for the specific luminance

A field on the road surface is chosen on basis of the following considerations. On one hand the field is to be of such dimensions compared to those of the surface texture that the field represents the surface adequately. The field must be so small, on the other hand that the angles of the geometry, $\varepsilon$, $\alpha$ and $\beta'$ are approximately constant for all points in the field.

This field of the surface defines a reference plane, in relation to which the angles of geometry are defined. The surface itself is, however, not plane,
but has a texture both on a macro-scale and a micro-scale. See fig. B.1.

Figure B.1 Choice of a field on the road surface. The field has, on one hand, to be so large as to represent the surface texture adequately, and, on the other hand, so small compared to other dimensions of the geometry that the angles of geometry are constant for all points in the field. The angles of the measuring geometry are defined relatively to a reference plane.

Valg af felt på vejbelægningens overflade. Feltet skal på den ene side være så stort, så det repræsenterer overfladeteksturen tilstrækkeligt godt, og på den anden side så lille i sammenligning med geometriens dimensioner, at geometriens vinkler er konstante for alle punkter i feltet. Målegeometriens vinkler fastlægges relativt til feltets reference plan.
In order to facilitate the discussion, the surface is divided into small, plane facets. This division has to be so fine that even the micro-texture of the surface is split up into plane parts. The division further has to be so fine that it is a good approximation to ignore phenomena of partly illuminated or partly visible facets. See fig. B.2.

Figure B.2 The surface of the field is divided into a number of small, plane facets. When this division is sufficiently fine, any facet is considered to be either fully illuminated, or not illuminated at all, and fully visible, or not visible at all.

Hence a facet is considered to be either fully illuminated all over its surface or not illuminated at all. Similarly, a facet is completely visible or not visible at all.

The totality of facets in the field is numbered from one to the total number of facets. The index, i serves for this numbering and means, simultaneously, any facet in the field.

The reflection properties of a facet are described
by a luminance coefficient, \( q_i \), which might in principle vary with the angles of geometry. The area of a facet is called \( a_i \).

The important aspect of the orientation of a facet is the orientation relative to the directions of illumination and observation. The angles between the normal of the facet and the directions of illumination and observation are called respectively \( u_i \) and \( v_i \) in the following. See Fig. B.3 regarding these angles and other properties of the facets.

![Diagram](https://via.placeholder.com/150)

**Figure B.3** The important aspects of the orientation of a facet (No. i) are the angles \( u_i \) and \( v_i \) between the normal of the facet and the directions of illumination and observation. Other properties of a facet are its area, \( a_i \) and its luminance coefficient, \( q_i \).

De vigtigste forhold ved orienteringen af en facet (nr. i) er vinklerne \( u_i \) og \( v_i \) mellem facetternes normal og belysnings- samt observationsretning. Andre af facetternes egenskaber er dens areal, \( a_i \) og dens luminanskoefficient, \( q_i \).

A facet is illuminated, when it is inclined towards the direction of illumination (when \( \cos u_i > 0 \)), with the further requirement that the facet is not in the shadow of other facets.

The subgroup of illuminated facets is numbered from one to the total number of such facets. For these facets is used the index \( j \).

As the number of illuminated facets clearly in-
creases, when the illumination angle increases, it is assumed that the index \( j \) always refers to the actual illumination angle and that the illuminated facets are renumbered, when this angle changes.

The illuminance on an illuminated facet is called \( E_j \) and found by:

\[
E_j = E_\perp \cdot \cos u_j
\]

where \( E_\perp \) is the illuminance on a plane perpendicular to the direction of illumination at the position of the facet.

To the illuminance \( E_\perp \) is remarked that the value is taken to be the same for all illuminated facets due to the assumption of a small field.

The illuminance on facets that are not directly illuminated is taken to be 0. This assumption and the expression for \( E_j \) given above shows that illumination by interreflection among the facets is disregarded. The validity of this simplification is discussed in section B.5.

The luminous flux, \( \phi_j \) on an illuminated facet is found by:

\[
\phi_j = a_j \cdot E_j = E_\perp \cdot a_j \cdot \cos u_j
\]

Thus the total luminous flux falling on the field, \( \phi \) is:

\[
\phi = E_\perp \cdot \sum_j a_j \cdot \cos u_j
\]

where the summation is for all illuminated facets (the subgroup of index \( j \)).
The total luminous flux can, however, also be computed by means of the illumination angle \( \varepsilon \) and the area, \( A \) of the reference plane of the field:

\[
\phi = E_\parallel \cdot A \cdot \sin \varepsilon = E_\parallel \cdot \sum_j a_j \cdot \cos \varepsilon_j
\]

This shows that:

\[
\sum_j a_j \cdot \cos \varepsilon_j = A \cdot \sin \varepsilon
\]

It is convenient for later use to introduce a normalized area, \( a'_1 \), of facets by means of:

\[
a'_1 = a_1 / (A \cdot \sin \varepsilon)
\]

Hence it is obtained that \( a'_j \cdot \cos \varepsilon_j \) means the fraction of the incident luminous flux that falls on facet No. \( j \) and that the sum of these fractions equals unity as shown below:

\[
\sum_j a'_j \cdot \cos \varepsilon_j = \frac{1}{A \cdot \sin \varepsilon} \sum_j a_j \cdot \cos \varepsilon_j = 1
\]

Only facets that are visible contribute to the luminance, \( L \) of the field as seen by the observer. Also this subgroup of facets is assumed to be numbered and to be distinguished by a special index, \( k \) running from one to the total number of such facets. This subgroup is further assumed to be redefined and renumbered each time the observation angle is changed. See fig. B.4.

The luminance of a visible facet, \( L_k \) is given by:

\[
L_k = \begin{cases} 
q_k \cdot E_k & \text{if the facet is illuminated (belongs also to the group with index } j) \\
0 & \text{otherwise}
\end{cases}
\]
This shows that it is convenient to introduce the further subgroup of facets that are illuminated and also visible. This subgroup is distinguished by the index 1 and is to be redefined at any change in the geometry of illumination and observation.

Figure B.4 A facet is illuminated, when it is inclined towards the headlight (when \( \cos u_i > 0 \)) and simultaneously not in the shadow of other facets. Similarly a facet is visible, when it is inclined towards the observer (when \( \cos v_j > 0 \)) and simultaneously not hidden behind other facets. Illuminated facets are given the index \( j \), visible facets the index \( k \), while facets that are both illuminated and visible are given the index \( l \).

En facet er belyst, når den hælder imod billygten (når \( \cos u_i > 0 \)) og samtidigt ikke ligger i skyggen af andre facetter. Tilsvarende er en facet synlig, når den hælder mod observatøren (når \( \cos v_j > 0 \)) og samtidig ikke er skjult bag andre facetter. Belyste facetter gives indekset \( j \), synlige facetter indekset \( k \), mens facetter, som er både belyste og synlige gives indekset \( l \).
As the apparent area of a visible facet is \( a_k \cdot \cos v_k \),
the total intensity \( I \) of light reflected towards the observer, is:

\[
I = \sum \frac{E_k \cdot A \cdot \sin \epsilon \cdot a'_l \cdot q'_l \cdot \cos u'_l \cdot \cos v'_l}{A \cdot \sin \alpha}
\]

Further, the total apparent area of the field is \( A \cdot \sin \alpha \) and the luminance \( L = I/(A \cdot \sin \alpha) \). Thus, the specific luminance, \( SL \) is finally given by this expression:

\[
SL = \frac{L}{E_l} = \frac{I}{E_l \cdot A \cdot \sin \alpha}
\]

where the summation is for all facets that are illuminated and also visible.

This expression is modified and interpreted in the following sections. The derivation of the expression is summarized in fig. B.5.

**B.3 - Average luminance coefficient**

An average luminance coefficient, \( \bar{q} \) is defined by:

\[
\bar{q} \cdot \sum \frac{E_a \cdot a'_l \cdot \cos u'_l \cdot \cos v'_l}{\sin \alpha} = \sum \frac{E_a \cdot a'_l \cdot q'_l \cdot \cos u'_l \cdot \cos v'_l}{\sin \alpha}
\]

where the summations are for all facets that are illuminated and also visible.

Introducing \( \bar{q} \) into the expression for \( SL \), this expression is changed into:

\[
SL = \bar{q} \cdot \frac{\sin \epsilon}{\sin \alpha} \cdot \sum \frac{E_a \cdot a'_l \cdot \cos u'_l \cdot \cos v'_l}{\sin \alpha}
\]
The luminous intensity of reflected light from a facet, which is illuminated and visible, is:

\[ I_k = E_\perp \cdot a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1 \]

The total luminous intensity, \( I \), is obtained by summation for all facets of index \( k \), and the specific luminance can be computed:

\[ SL = \frac{1}{A \cdot \sin \alpha} \cdot \frac{1}{E_\perp} = \frac{1}{A \cdot \sin \alpha} \sum a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1 \]

\[ SL = \frac{\sin \varepsilon}{\sin \alpha} \cdot \sum a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1 \]

where \( A \) is the area of the field measured in the reference plane, and \( A \cdot \sin \alpha \) is the apparent area, and \( a'_1 = a_1/(A \cdot \sin \varepsilon) \) is a normalized area of the facet.

Lysstyrken af det reflekterede lys fra en facet, som er både belyst og synlig, er:

\[ I_k = E_\perp \cdot a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1 \]

Den totale lysstyrke fra feltet, \( I \), fås ved summation for alle facetter med indeks \( k \), og den specifikke luminans kan beregnes til:

\[ SL = \frac{1}{A \cdot \sin \alpha} \cdot \frac{1}{E_\perp} = \frac{1}{A \cdot \sin \alpha} \sum a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1 \]

\[ SL = \frac{\sin \varepsilon}{\sin \alpha} \cdot \sum a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1 \]

hvor \( A \) er arealet af feltet målt i referenceplanet, og \( A \cdot \sin \alpha \) er det tilsyneladende areal, og \( a'_1 = a_1/(A \cdot \sin \varepsilon) \) er facetten's normerede arealet.
This modification of the expression for $\overline{SL}$ is a convenient one, when the value of $\bar{q}$ is relatively insensitive to variations in the geometry of illumination and observation.

One source for a variation of $\bar{q}$ with the geometry would be a possible variation of the individual $q_1$ of the facets.

It is, however, demonstrated in section B.5 that the major part of $\overline{SL}$ is caused by facets of a large inclination. For these facets the luminance coefficients are certainly determined mainly by a diffuse type of reflection, and the values are not likely to change significantly within the small angular ranges of the interesting geometries.

Therefore, $\bar{q}$ will hardly change significantly because of changes in the individual $q_1$.

Another source of variation of $\bar{q}$ could be a variation of the factors to the $q_1$ in the sums.

One of these factors is the scaled area of the facet $a'_1$, which changes with the angle of illumination, $\varepsilon$, see section B.2. As the $a'_1$ all changes by the same factor, these changes will not affect the value of $\bar{q}$.

The other factors are cosines, which for the facets of large contributions to $\overline{SL}$ have relatively large values. The rate of change of these cosines with the angles will, therefore, be small relative to the values of the cosines themselves.

The factors to the individual $q_1$ can, therefore, hardly introduce rapid changes in the value of $\bar{q}$.

The final possible source of variation of the value of $\bar{q}$ is the change of the subset of illuminated and
visible facets (those with index 1) that will result from a change in the geometry.

Clearly, a change in the subset of the facets is not important, when all facets that can be illuminated, have similar $q_1$. This is the case, when all the stones in the surface are of a uniform and similar lightness.

Further, a change in the subset of the facets is not important, when facets of dissimilar $q_1$ are placed randomly in the texture, so that their relative populations do not change. Surfaces of this property could have stones that are similar, but each with patterns of lightness. Surfaces would have this property also, even when the stones vary in lightness, when only this variation is not coupled with a systematic variation in size, shape or position in the surface.

Most road surfaces can, therefore, be expected to have a $\bar{q}$, whose value reflects the lightness or perhaps the average lightness of the stone material in the surface, and whose value is relatively insensitive to changes in the geometry of illumination and observation.

Some surfaces will, on the other hand, show significant changes in $\bar{q}$, but these changes relate in a natural way to the properties of the surface. An example of such a surface is shown in fig. B.6.

**B.4 - Factor of geometry**

The expression for $SL$ contains a factor, which is the ratio of the sinus of the illumination angle, $\epsilon$ and the sinus of the observation angle, $\alpha$.

This factor obviously changes with the lighting geometry, and does, as it will appear from the fol-
A. A surface with light coloured stones in a dark coloured base

EN OVERFLADE MED LYSE STEN I EN MØRK MATRIX

B. At small illumination angles, $\varepsilon$ only the light coloured stones are illuminated

VED SMÅ BELYSNINGSVINKLER, $\varepsilon$ ER KUN DE LYSE STEN BELYSTE

C. At large illumination angles, $\varepsilon$ parts of the dark coloured base are illuminated

VED STORE BELYSNINGSVINKLER, $\varepsilon$ BELYES DELE AF DEN MØRKE MATRIX

Figure B.6 The average luminance coefficient, $\bar{q}$, is an average of the luminance coefficients of facets that are illuminated and visible defined by:

$$\bar{q} \cdot \sum a_1 \cdot \cos u_1 \cdot \cos v_1 = \sum a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1$$

A surface with light coloured stones in a dark coloured base (fig. a.) will have a large $\bar{q}$ at small illumination angles (fig. b.) and a smaller $\bar{q}$ at large illumination angles (fig. c.).

Den gennemsnitlige luminanskoefficient, $\bar{q}$, er et gennemsnit af luminanskoefficienten for facetter, som er belyste og synlige:

$$\bar{q} \cdot \sum a_1 \cdot \cos u_1 \cdot \cos v_1 = \sum a_1 \cdot q_1 \cdot \cos u_1 \cdot \cos v_1$$

En overflade med lyse sten i en mørk matrix (fig. a.) vil have en høj $\bar{q}$ ved små belysningsvinkler (fig. b.) og en lavere $\bar{q}$ ved store belysningsvinkler (fig. c.).
lowing sections, account for the major part of the influence of the geometry. An appropriate name for this factor is, therefore, factor of geometry, $f_{\text{geometry}}$:

$$f_{\text{geometry}} = \frac{\sin c}{\sin a} = \frac{c}{a} = \frac{H_h}{H_o} \cdot \frac{D_o}{D_h}$$

The factor of geometry is thus easily determined from the geometry of illumination and observation. At medium and large distances the factor further approximately equals the ratio between the headlight mounting height, $H_h$ and the observer eye height, $H_o$:

$$f_{\text{geometry}} \approx \frac{H_h}{H_o} \quad \text{at medium and large distances}$$

A simple interpretation of this factor is given in fig. B.7.

**B.5 - Factor of texture**

**B.5.1 - Definition of the factor of texture**

According to the previous sections, the expression for SL reads as follows:

$$SL = \bar{\sigma} \cdot f_{\text{geometry}} \cdot \sum_{l=1}^{j} \cdot \cos u_l \cdot \cos v_l$$

where the summation is for all facets that are illuminated and also visible.

The group of facets of index 1 can be thought of as containing facets that are illuminated, excluding those facets that are illuminated, but not visible. The first-mentioned group (illuminated facets) has already been given the index $j$; the last-mentioned group (illuminated, but not visible facets) is given the index $m$. 
Figure B.7 The factor of geometry, \( f_{\text{geometry}} = \frac{\sin \alpha}{\sin \alpha} \) approximately gives the fraction of the apparent area of the field, which is filled with illuminated facets.

In this way, the SL expression is changed into:

\[
SL = \bar{q} \cdot f_{\text{geometry}} \cdot f_{\text{texture}} \cdot f_{\text{visible}}
\]

where \( f_{\text{texture}} = \sum_j a'_j \cdot \cos u_j \cdot \cos v_j \)

and \( f_{\text{visible}} = 1 - \frac{1}{f_{\text{texture}}} \cdot \sum_m a'_m \cdot \cos u_m \cdot \cos v_m \)
The factor of visible, illuminated facets, $f_{\text{visible}}$ is discussed in the next section, while the factor of texture, $f_{\text{texture}}$ is the aim of discussion of this section.

**B.5.2 Range of variation of the factor of texture**

In interpreting the expression for $f_{\text{texture}}$ it is to be recalled that the products of the first two factors of the terms are the fractions of the incident luminous flux that fall on the facets. The third factor is the cosine of the angle between the normal of the facet and the direction towards the observer. This cosine represents the inclination of the facet towards the observer.

Broadly speaking $f_{\text{texture}}$ is then the average inclination of facets towards the observer, as weighted by the incident luminous flux on the facets.

As the highest possible value of the third factor is unity, and as the sum of the weights (the product of the first two factors) is also unity, the highest possible value of $f_{\text{texture}}$ is unity.

The lowest possible value of the third factor is of course zero for a visible facet (otherwise the facet would not be visible). As the angular separation between the observer and the headlight is small in all interesting situations, the lower limit of the third factor is appr. zero also for all illuminated facets. For practical applications it is assumed, therefore, that the lower limit of $f_{\text{texture}}$ is zero:

$$0 \leq f_{\text{texture}} \leq 1$$

The value actually taken by $f_{\text{texture}}$ is obviously a matter of the texture of the surface, which explains the choice of name and notation for the factor. In principle the value can be a function of the geometry.
also, as directions of illumination and observation enter via the cosines of the terms of the sum, and as the direction of illumination determines what facets are to be included into the sum.

It is, therefore, perhaps somewhat surprising that the results of measurements can be explained only by assuming that $f_{\text{texture}}$ is roughly independent of the geometry. It is further surprising that the value of $f_{\text{texture}}$ is quite high, a substantial fraction of unity, considering the large angles formed between the normal of the reference plane of the surface and the directions towards the headlight and the observer.

The aim of the following is to explain these conclusions of the measurements, pointing out that even a smooth road surface has some texture, and that the special geometry leads to a strong emphasis on those facets that have an inclination towards the vehicle. See fig. B.8.

**B.5.3 - The factor of texture in relation to the surface texture**

The most obvious surface to consider is a perfectly plane and smooth (polished) surface.

For this surface $f_{\text{texture}}$ is as shown in fig. B.9 computed to $\sin \alpha$, and thus has a value of appr. 0.1 at short distances decreasing to appr. 0.01 at large distances. The corresponding behaviour of SL would be a low value decreasing to very small values at large distances.

This behaviour of SL is in contradiction with the measurements, which show larger values of SL that are maintained even at large distances. The assumption of a plane and smooth surface is even in strong disagreement with the observations, as such a surface
A. A FACET OF A SMALL INCLINATION HAS A SMALL CONTRIBUTION TO $f_{\text{TEXTURE}}$, as $\cos u_j$ and $\cos v_j$ are both small.

EN FACET MED EN LILLE HÆLDNING GIVER ET LILLE BIDRAG TIL $f_{\text{TEXTURE}}$, DA $\cos u_j$ OG $\cos v_j$ BEGGE ER SMÅ.

Figure B.8 The factor, $f_{\text{TEXTURE}}$, is the sum of $a'_j \cdot \cos u_j \cdot \cos v_j$ for all illuminated facets (index $j$). The maximum value is unity. Facets of a small inclination towards the vehicle give a small contribution (fig. a.), while facets of a large inclination give a relatively large contribution (fig. b.).

Paktoren, $f_{\text{TEXTURE}}$, er summen af $a'_j \cdot \cos u_j \cdot \cos v_j$ for alle belyste facetter (index $j$). Den maximale værdi er en. Facetter med en lille hældning mod køretøjet giver et lille bidrag (fig. a.), mens facetter med en stor hældning giver et relativt stort bidrag (fig. b.).
would show Fresnel-type properties with small values of $q$ decreasing with distance.

The assumption of a plane and smooth surface is, therefore, not valid. This can be considered a good piece of fortune, as such a surface would have extremely low SL-values, in particular at large distances, and could hardly be given any useful luminance by headlight illumination.

![Diagram](image)

**Figure B.9** A perfectly plane and smooth surface is illuminated all over and has a cosv of $\cos(90°-\alpha) = \sin\alpha$. Hence $f_{\text{texture}}$ is $\sin\alpha$ for this surface.

En fuldståndig plan og glat overflade er belyst på hele overfladen og har en cosv lig med $\cos(90°-\alpha) = \sin\alpha$. Faktoren, $f_{\text{texture}}$ er således $\sin\alpha$ for denne overflade.

In the other extreme, one could consider a surface, in which all the illuminated facets are vertical and turned towards the observer and the headlight, see fig. B.10. This assumption leads to a $f_{\text{texture}}$, which in agreement with observations is independent of the geometry, but whose value is clearly to large, being close to unity.

A natural modification of this model of vertical facets is to assume that the illuminated facets are vertical but otherwise of a random orientation, e.i.: that they put together can form the front half of a vertical cylinder. Even with this modification the result remains essentially as given above. The
factor, $f_{\text{texture}}$ is approximately constant with a value reduced to 0.79, but still too large to explain observations.

![Diagram of a surface with illuminated facets]

**Figure B.10** A surface, whose illuminated facets are all vertical and turned towards the observer, has facets of $a \cos v = \cos \alpha$. Hence $f_{\text{texture}} = \cos \alpha \approx 1$ for interesting geometries.

En overflade, hvis belyste facetter alle er lodrette og orienteret imod observatøren, har facetter hvis $\cos v = \cos \alpha$. Derfor er faktoren, $f_{\text{texture}} = \cos \alpha \approx 1$ for relevante geometrier.

A combination of the two extremes of respectively horizontal and vertical facets can give a better account of the observations.

Such a combined model could have vertical facets of a random orientation receiving say 40% of the incident luminous flux and horizontal facets receiving the remaining 60% of the luminous flux. In such a model the vertical facets will contribute a constant value of 0.30 to $f_{\text{texture}}$, while the horizontal facets will contribute a variable, but much smaller value.

For the vertical facets to receive 40% of the luminous flux, their area needs to be quite small only (e.g. 2% of the area of the horizontal facets at an illumination angle of 1°). Thus the dominating contribution of the vertical facets to $f_{\text{texture}}$ is achieved, even when they are not obviously important in the texture.
In a more realistic model one has to consider illuminated facets of all possible angles. Such models are not considered here in detail, but conclusions are very similar to those given above, when "vertical facets" are understood as facets with a large inclination and "horizontal facets" are understood as facets with a small inclination.

In conclusion the special geometry of illumination and observation will single out some facets of a large inclination to receive a significant part of the incident luminous flux and to give a dominant contribution to $f_{\text{texture}}$ and thus to the SL of the surface.

It appears from the discussion above that when a constant fraction of the incident luminous flux falls on facets of a large inclination, $f_{\text{texture}}$ will remain essentially constant.

This shows that $f_{\text{texture}}$ should to a good approximation be independent of the observation angle $\alpha$ (and of the angle $\beta'$), since the illumination angle, $\epsilon$, alone determines what facets are illuminated.

Obviously the fraction of luminous flux falling on facets of a large inclination, must be roughly independent of the illumination angle $\epsilon$ also, as the measurements can be explained by the assumption of a roughly constant $f_{\text{texture}}$.

Intuitively one would think that facets of a large inclination are found mainly in the lower parts of the surface texture, and that these can be illuminated at relatively large illumination angles only. Hence one could expect a decrease in $f_{\text{texture}}$ at decreasing illumination angles (at increasing distance).
This decrease in $f_{\text{texture}}$ with $\varepsilon$ is, however, not observed in general, which shows that even at small $\varepsilon$ the illumination of facets with large inclinations does occur. One reason for this could be that such facets exist also in the upper part of the texture, perhaps due to micro-texture or to variations in the size of stones. Another reason could be that the random arrangement of the stones in the surface leaves "paths" for light to penetrate down into the texture even at small illumination angles.

It is thus to be concluded that $f_{\text{texture}}$ is roughly independent of the angles of the geometry. This leaves the factor $f_{\text{geometry}}$ to give the main account of the influence of the angles $\varepsilon$ and $\alpha$. A further influence of these angles is discussed in the next section.

The factor, $f_{\text{texture}}$ can then be considered to be a function mainly of the surface texture.

The important aspect of the texture is what fraction of the luminous flux that will fall on facets of a large inclination. This is a result of relative proportions of the texture and not of the dimensions of stones, edges etc.

The correlation between $f_{\text{texture}}$ and the traditional measure of the texture by means of the texture depth (sand-patch method) need, therefore, not to be good.

This is probably the reason that some attempts to correlate SL to the texture depth did not succeed. However, different types of surfaces can have values of $f_{\text{texture}}$ at different levels and also different ranges of texture depths, thus giving an indirect correlation. See Sørensen and Nielsen (1975) and Mørkertrafik Report No. 2 (1978).
B.5.4 - Interreflections in the texture

The discussion above gives a clue as to why interreflection in the texture has been ignored.

The fact that $f_{\text{texture}}$ is quite large, is a sign that the direct illumination is effectively reflected back towards the observer. The name retroreflection used for SL at some occasions has in fact some justification.

The reflected luminous flux does not possess this efficiency, as it falls on the more numerous non-visible facets as well as on visible facets. Only a small fraction will fall on visible facets with a large inclination towards the observer.

Further, the secondary luminous flux to fall on the surface is reduced compared to the direct luminous flux by reflection losses and by escape upwards, away from the surface. The first-mentioned reduction is large for common, dark surfaces, while the last-mentioned reduction must always be large.

For these reasons, interreflections in the texture can hardly raise the SL of road surfaces by more than a very small amount.

B.6 - Factor of illuminated, visible facets

B.6.1 - Definition of factor of illuminated, visible facets

In section B.5.1 was introduced a factor of illuminated, visible facets, $f_{\text{visible}}$ defined by:

$$f_{\text{visible}} = 1 - \frac{1}{f_{\text{texture}}} \sum_{m} a' \cdot \cos u \cdot \cos v_m$$

where the summation is for all facets that are illuminated, but not visible.

When none of the illuminated facets are visible,
\( f_{\text{visible}} \) has the lowest possible value of zero, and when all of the illuminated facets are visible, the highest possible value of unity is attained. Thus

\[ 0 \leq f_{\text{visible}} \leq 1 \]

**B.6.2 - The situation, when \( \beta' = 0^\circ \) (as for a motorcyclist)**

As illustrated in fig. B.11 an edge of an illuminated facet has a shadow, which lies higher than the edge, when \( \alpha > \varepsilon \) and also \( \beta' = 0^\circ \). Therefore, in this geometry there can be no illuminated facets hiding below the edge, i.e.: behind the facet.

A facet, which is in the shadow behind other facets, cannot either hide an illuminated facet, because the argument given above applies, if the facets in the front are removed.

Further, a facet, which is not inclined towards the headlight, will always be in the shadow of other facets, which are inclined towards the headlight.

It is, therefore, also impossible for such facets to hide an illuminated facet.

As there are no facets that do not belong to one of the above-mentioned categories, it is concluded that for \( \alpha > \varepsilon \) and \( \beta' = 0^\circ \) all illuminated facets are visible, and hence:

\[ f_{\text{visible}} = 1 \ \text{for} \ \alpha > \varepsilon, \ \text{when also} \ \beta' = 0^\circ \]

An implicit assumption behind fig. B.11 is that all free edges in the texture (those that define contours of stones) are at most vertical. This seems a reasonable assumption, as the texture should otherwise show paths for illumination, which have "roofs" as for instance shown by a hole in a stone or by an overhang. It is possible that such paths can occasionally be found, but hardly in numbers to signifi-
cantly reduce the validity of the statement given above.

Figure B.11 The edge of an illuminated facet casts a shadow on a background in a distance, \( S \) behind the edge. As the shadow lies above the edge by \( S \cdot \tan(\alpha - \epsilon) \), there can be no illuminated facets behind the facet with the edge. In reality the distance to the background, \( S \) will vary along the edge, giving the shadow of the edge a irregular shape, but still lying above the edge at all points.

In the geometry experienced by a motorcyclist, \( f_{\text{visible}} \) is, therefore, unity.

A hiding of illuminated facets and hence a reduction of \( f_{\text{visible}} \) is certainly to be expected, if the mo-
torcyclist lowers his head below his headlight (if this is possible) so that a situation of \( \alpha < \varepsilon \) and \( \beta' = 0^\circ \) occurs. Another way to achieve this situation is for a driver to turn on a searchlight on the roof of the car.

The reason that there must be non-visible illuminated facets for \( \alpha < \varepsilon \) is that the sum of the apparent areas of illuminated facets is larger than the apparent area of the field, and therefore, cannot be contained in this area.

At \( \alpha = \varepsilon \) and \( \beta' = 0^\circ \) the two above-mentioned areas match perfectly and all illuminated areas are also visible and vice versa. At a further decreasing \( \alpha \), the apparent area of the field decreases and more and more illuminated facets must become hidden. At \( \alpha = 0^\circ \) no facets are in principle visible as the total apparent area is zero. Therefore (see fig. B.12):

\[
\begin{align*}
\text{for } \beta' &= 0^\circ \\
\text{for } \beta' &= 0^\circ \\
\text{for } \beta' &= 0^\circ \\
\end{align*}
\]

\[
\frac{f_{\text{visible}}}{= 1 \text{ for } \alpha \geq \varepsilon} \quad \text{decreases for } \alpha < \varepsilon \quad \frac{f_{\text{visible}}}{= 0 \text{ for } \alpha = 0^\circ}
\]

The decrease of \( f_{\text{visible}} \) for decreasing \( \alpha \) must further occur in such a manner as to counteract the increase in \( f_{\text{geometry}} \). Probably the product of \( f_{\text{geometry}} \) and \( f_{\text{visible}} \) is roughly constant for \( \alpha < \varepsilon \), so that the road surface luminance is approximately constant.

**B.6.3 - The situation of \( \beta' \neq 0^\circ \) (as for a car driver)**

A more interesting situation is, however, the one of \( \alpha > \varepsilon \) and \( \beta' \neq 0^\circ \). For a common vehicle the headlight in the steering side will have a small \( \beta' \), while the headlight in the other side has a \( \beta' \) comparable to the other angles of the geometry.
A. WHEN THE FIELD IS SEEN FROM A POINT ABOVE THE HEADLIGHT, ALL ILLUMINATED STONES ARE VISIBLE AND SEEN ON THE BACKGROUND OF THEIR OWN SHADOWS

NÅR FELTET SES FRA ET PUNKT OVER LYGTEN, ER ALLE BELYSTE STEN SYNLIGE OG SES PÅ BAGGRUND AF DERES EGNE SKYGGER

B. WHEN THE FIELD IS SEEN FROM THE POSITION OF THE HEADLIGHT, THE ILLUMINATED STONES ARE PRECISELY ALSO VISIBLE

NÅR FELTET SES FRA LYGTENS POSITION, ER DE BELYSTE STEN NETOP SYNLIGE

C. WHEN THE FIELD IS SEEN FROM A POINT BELOW THE HEADLIGHT, NOT ALL OF THE ILLUMINATED PARTS (FACETS) OF THE STONES ARE VISIBLE

NÅR FELTET SES FRA ET PUNKT UNDER LYGTEN, ER IKKE ALLE DELE (FACETTER) AF STENENE SYNLIGE

Fig. B.12 The factor, $f_{\text{visible}}$, accounts for what fraction of illuminated facets are also visible.

In the situation as for a motorcyclist ($\beta' = 0^\circ$) all illuminated facets are visible and hence $f_{\text{visible}} = 1$ (figs. a. and b.), except if the point of observation is below the headlight (fig. c.).

Faktoren, $f_{\text{visible}}$, er den brøkdel af de belyste facetter, som også er synlige. I situationen, som for en motorcyklist ($\beta' = 0^\circ$) er alle belyste facetter synlige og derfor $f_{\text{visible}} = 1$ (fig. a. og b.), undtagen hvis observationspunktet ligger under lygten (fig. c.).
As shown in fig. B.13, $\beta'$ can change somewhat and still leave an illuminated facet on the background of its own shadow. When $\beta'$ increases further, some of the illuminated facets will become hidden and thus not visible, and $f_{\text{visible}}$ will decrease. See fig. B.14.

At large $\beta'$ the ordered arrangement between illuminated facets and shadows, which was found at $\beta' = 0^\circ$, breaks down and it becomes a random event, whether the background behind a facet is illuminated or not.

The value of $f_{\text{visible}}$, which is found at large $\beta'$, must have some bearing on the population of illuminated facets in the background behind other facets. This population (and thus the value of $f_{\text{visible}}$ at large $\beta'$) is clearly not a function of $\beta'$, but of the other angles of geometry.

According to this, the expression for $f_{\text{visible}}$ is rearranged to:

$$f_{\text{visible}} = 1 - F_1 \cdot F_2 \quad \text{for } \alpha > \epsilon$$

where $F_1$ is a sort of threshold function ($0 \leq F \leq 1$) and

$$F_2 = \frac{1}{F_{\text{texture}}} \cdot \max (\sum_{m} a'_m \cdot \cos u_m \cdot \cos v_m)$$

By the maximum sum in the expression for $F_2$ is meant the sum found at the relevant $\alpha$ and $\epsilon$ and at a numerically large $\beta'$. $F_1$ is a measure of what fraction of the maximum sum of $F_2$ is found at the relevant $\beta'$.

$F_1$ must clearly be a function of a parameter, $p_1$ which contains $\beta'$. It is tempting according to fig. B.13 to use:

$$F_1 = F_1(p_1)$$

where $p_1 = \left| \frac{\beta'}{\alpha - \epsilon} \right|$
Figure B.13 For $\beta' = 0^\circ$ the shadow of an edge of an illuminated facet lies $S \cdot \tan(\alpha-\varepsilon)$ above the edge, or a distance of $S \cdot \tan(\alpha-\varepsilon)/\tan\theta$ transverse to the edge ($S =$ distance to background; $\theta =$ angle of edge to the horizontal).

When the observer moves ($\beta' \neq 0^\circ$), the edge and its shadow shift relative to each other in the transverse direction by $S \cdot \tan\beta'$.

The edge will reach its shadow at:

$$\tan\beta' = \frac{\tan(\alpha-\varepsilon)}{\tan\theta}$$

or

$$\frac{\tan\beta'}{\tan(\alpha-\varepsilon)} = \frac{\beta'}{\alpha-\varepsilon} = \frac{1}{\tan\theta}$$

For $\beta' = 0^\circ$ ligger skyggen af en kant af en belyst facet højden $S \cdot \tan(\alpha-\varepsilon)$ over kanten, og derfor en afstand på $S \cdot \tan(\alpha-\varepsilon)/\tan\theta$ til siden for kanten ($S =$ afstand til baggrunden; $\theta =$ kantens vinkel med værned). Når observatøren bevæger sig ($\beta' \neq 0^\circ$), flytter kanten og dens skygge til siden i forhold til hinanden med $S \cdot \tan\beta'$. Kanten falder sammen med sin skygge ved:

$$\tan\beta' = \frac{\tan(\alpha-\varepsilon)}{\tan\theta}$$

ell.

$$\frac{\tan\beta'}{\tan(\alpha-\varepsilon)} = \frac{\beta'}{\alpha-\varepsilon} = \frac{1}{\tan\theta}$$
A. AN ILLUMINATED STONE IN THE FIELD AS SEEN FROM A POINT ABOVE THE HEADLIGHT

EN BELYST STEN I FELTET SOM SET FRA ET PUNKT OVER LYGTERN

B. THE POINT OF OBSERVATION IS SHIFTED SOMewhat TO THE LEFT OF THE HEADLIGHT

OBSERVATIONSPUNKET ER FLYTTET LIDT TIL VENSTRE FOR LYGTERN

C. THE POINT OF OBSERVATION IS SHIFTED FURTHER TO THE LEFT, AND A PART OF THE STONE IS OUTSIDE ITS SHADOW

OBSERVATIONSPUNKET ER FLYTTET FYDERLIGERE TIL VENSTRE, HVORVED EN DEL AF STENEN LIGGER UDEN FOR SIN SKYGGE

**Figure B.14** When the point of observation is directly above the headlight ($\beta' = 0^\circ$, fig. a.) or when the point is shifted only little ($\beta' \text{ small}$, fig. b.) all illuminated stones are seen on the background on their own shadows, hence $f_{\text{visible}} = 1$. At a sufficiently large shift (fig. c.) the illuminated stones can hide each other and $f_{\text{visible}} < 1$.

Når observationspunktet ligger lige over lygten ($\beta' = 0^\circ$, fig. a.), eller når det kun er flyttet lidt ($\beta' \text{ lille}$, fig. b.), ses alle belyste sten på baggrund af deres egne skygger og $f_{\text{visible}} = 1$. Ved en tilstrækkelig stor flyttning (fig. c.) kan de belyste sten skjule hinanden og $f_{\text{visible}} < 1$. 


It is further reasonable to assume that $F_1$ is zero for $p_1 = 0$ and increases asymptotically to unity for increasing $p_1$ with a steep increase around $p_1 = 1$.

$F_2$ is a function of a parameter, $p_2$ which, as mentioned above, includes $\alpha$ and $\varepsilon$, but not $\beta'$.

The depth into the texture, into which there are illuminated facets, increases undoubtedly with $\varepsilon$. This depth is, however, larger than indicated by $\varepsilon$ as there are paths in the disordered texture, into which the incident light can penetrate deeper. It is assumed that the total depth into the texture of illuminated facets is given by $\varepsilon$ plus an additional angle $p'_2$, which is characteristic of the texture.

The depth into the texture in which the observer can see illuminated facets is given, on the other hand, by $\alpha$. In this case $p'_2$ cannot be considered to increase the depth, as the paths into the texture for observation are not identical to those for illumination ($\beta'$ is not zero). The paths into the texture for observation should, therefore, not often turn up to show illuminated facets.

These arguments lead to:

$$F_2 = \begin{cases} \text{small, when } & \alpha - \varepsilon > p'_2 \\ \text{increasing, when } & \alpha - \varepsilon \text{ decreases} \end{cases}$$

Without further arguments $\alpha - \varepsilon$ is used as the parameter $p_2$. The reason for this is mainly that this choice can explain the result of the measurements.

The function $F_2$ is then considered a function of $p_2$:

$$F_2 = F_2(p_2)$$

where $p_2 = \alpha - \varepsilon$
The largest value to be considered for $F_2$ is the one found for $\alpha - \varepsilon = 0^\circ$. This value has to be at most unity, but should in practice be smaller.

The estimation of the functions $F_1$ and $F_2$ is to be done on the basis of measurements.