REFLECTION PROPERTIES OF ROAD SURFACES

Contribution to OECD Scientific Expert Group AC4 on Road Surface Characteristics

R-83-52
Dr. D.A. Schreuder
Leidschendam, 1983
Institute for Road Safety Research SWOV, The Netherlands

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1. CHARACTERISATION

1.1. Introduction

The road surface forms an important part of the visual scene of road users of all classes. We will concentrate in the following on drivers of automobiles but the same generally holds true for truck drivers, riders of bicycles, motorcycles or mopeds, and even to a large extent for pedestrians.

The importance of the road surface in the visual scene has five aspects:

- the brightness of the road surface determines to a large extent the state of adaptation of the eye;
- the road surface forms the background for most of the objects (or obstacles) on the road that may endanger traffic;
- the round alignment is enhanced by the contrast between the road surface, the road edge and the edge markings;
- the surface of the road itself forms the most important aspect of the course of the route (the run of the road);
- the road surface constitutes the background for horizontal road markings as well as for raised pavement markers.

These five aspects are important under all prevailing conditions of lighting, the most of them being: daylight, lighting at night by means of street lights (public lighting) and the lighting by means of headlamps (vehicle lighting).

The brightness - or, more correct, by the luminance* - of the road surface is determined by the amount of light striking the surface, the reflection characteristics of the surface, and the geometric conditions (the directions in which the light is incident on the surface and the direction from which it is observed).

This chapter deals with these reflection characteristics, or, as they are sometimes called, the photometric characteristics.

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* The luminance is the objective quantification related to the subjective experience of brightness. It is expressed in candela per square metre and indicated usually by L (in cd/m^2).

This chapter will be not more than a brief introduction. The matter of the reflection properties of surfaces, and the more general matter of the technique and science of road lighting is discussed in great deal in the specialised literature (See e.g. De Boer (ed), 1967; SCW, 1974; CIE, 1973, 1976; OECD, 1980. Surveys of research in this area may be found in De Boer (ed), 1967; Sørensen & Nielsen, 1974; Sørensen, 1975).

To a casual observer pavement surfaces tend to appear matte or they seem to have a diffuse reflection. However under the real conditions of traffic, where the operator is viewing the pavement from an angle, the surface of the pavement is in fact highly specular and not matte at all. While this specularity is conspicuous when the pavement is wet, even in dry conditions all road surfaces are shiny. Thus, the observations of the casual observer may be quite misleading in making an assessment of the optical properties of road surface.

1.2. Representation of reflection properties in public lighting

The reflective properties of a road surface can be characterised by the luminance coefficient q. This coefficient is the ratio between the illuminance E** and the luminance L : q = L/E.
(It may be noted here that it is not quite certain whether q is dimensionless or not: experts do disagree whether L and E have the same dimension or not. This is the result of the fact that in the definition of L one has to incorporate the idea of the solid angle. In practice, there is no problem as one plays safe and expresses q in cd/m^2 per lux. In spite of many efforts, one has not been successful in making the photometric bases of illuminating engineering a little bit more tidy!).
q is a function of the geometry. As shown in Figure 1, when a small area

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** The illuminance E (or illumination) is a measure for the amount of light falling into a certain surface. The illuminance is expressed in lux (lx); its dimension is lumen per square meter.
So the illuminance E in P (see Figure 1) is:

$$E = \frac{I \cos \gamma}{AP^2} = \frac{I \cos \gamma}{H^2/\cos^2 \gamma} = \frac{I \cos^3 \gamma}{H^2}$$

of the surface (P) is illuminated by a source (a lamp) and observed by an observer (or a measuring device) 0, q depends upon α, β and γ. In some exceptional cases the road surface is not isotropic; this means that the position of 0 and P in relation to the lenghtwise axis of the road is important. However, generally, the influence of the angle can be neglected. Furthermore α is usually, rather arbitrarily, fixed at 1^{o} so that q depends only on the angles β and γ : q (β, γ). Incidentally, the convention $\alpha = 1^{o}$ indicates the very glancing angle that is relevant here, mainly for motor drivers, but to a large extent as well for other road users. Details of this approach are given by Schreuder (1967) and Jackett & Fisher (1974).

The reflection properties of this particular element of this surface P can be described completely in indicating the value of q for all relevant values of β and γ. In fact, this is precisely what is done if a complete lighting design is required. In most cases, however, less complete data are sufficient.

The element P must be small, otherwise the variations of α, β and γ within the dimension of the element cannot be neglected; however, it must not be too small either because, otherwise, the inherent irregularities of the road aggregates may cause too much spread in the measurements. Details are given in Chapter 2.

Another source of variation is the influence of the seasons. In most moderate climates the variation due to the seasons seems to be quite large; accurate, systematic measurements that can be applied in a general way, are, however, scarce.

The study of the reflection properties of road surfaces is a field of study with a long history. The first large scale, systematic study is the doctoral thesis of Bergmans (1938). Over many decades, however, progress was limited, because there was a lack of good, simple, accurate measuring equipment, and of fast, reliable (and cheap) calculating hardware. Only quite recently there is some progress.

Another problem was the fact that road surfaces differ immensely due to composition and construction. It has been a difficult job to establish a precise and accurate classification system of road surfaces. Finally, in spite of very clever experiments to prove otherwise, the only approach possible seems to be a phenomenological approach as fundamental studies regarding the reflection of road surfaces did not prove to be successful. The reason for this seems to be the glancing angle of observation. When the angle of observation is very slight, the overall reflection is determined to a large extent not by the surface or its aggregates, but by the voids between them. This proves to give rise to mathematical problems that cannot be surmounted, at least not analytically.

It has been indicated above that the complete representation of the reflection can be given by q as a function of β en γ. It may be added that, for convenience, usually the reduced luminance coefficient r defined as $r = q \cos^3 \gamma$ is used instead of q. Such a function can be measured directly by moving a lamp in respect to the sample in such a way that all relevant angles of β and γ are covered; and measuring (at $\alpha = 1^{o}$) the luminance for each combination of β and γ.
Usually some 400 combinations seem to be sufficient. By interpolation a grid can be arrived at. This grid is standardised by the CIE (1976). A more graphic representation is given in Figure 2. Here, the values of q are indicated for the respective angular values of β and γ and the result is a "solid body" or "indicatrix" which represents the complete reflection characteristic.
In such an indicatrix, the length of a vector drawn in a certain β and γ direction, gives the value of q for that β and γ combination. The shape of the indicatrix characterises the degree of specularity whereas the volume contained within it represents the level of the total reflectivity (the degree of lightness q_o is the average length of the vector). This representation is useful for qualitative considations. For quantitative work - e.g. the calculation of road surface luminances - a grid in table form is more useful. Further details are found in De Boer (ed), (1967).

For many applications a mass of data is required. Often however, it is quite sufficient to use a much smaller amount of measurements. Westermann (1963) was the first to propose a small number of characteristic numbers with the aim to characterise, not the road surface, but the reflection indicatrix. The idea came from the usual way to characterise a light beam; that is peak value, half-value width and "volume". This idea was applied to the indicatrix, and after some adaptation, Westermann proposed

q_o (average luminance coefficient) and k_p (specular factor). q_o can be described as

$$q_o = \frac{1}{\Omega_o} \int_o^{\Omega_o} q \, d\Omega$$

when Ω is the valid angle comprising the relevant β and γ-region; and $k_p = \log (q_o/q_p)$ when q_p is the CIE-value for perpendicular light incidence. A long, tedious and difficult discussion did lead finally to the proposal of Burghout (1977a) where only three judiciously selected q-values turn out to be sufficient to characterise a road surface. The three values are: the q-values belonging to:

a) perpendicular incidence ($\beta = 0, \gamma = 0$) represented by: q (0,0) or r (0,0) or q_p
b) $\beta = 0$; $tg\gamma = 2$ represented by: q (0,2) or r (0,2)
c) $\beta = 5$; $tg\gamma = 5$ represented by: q (5,5) or r (5,5)

We will come back in para. 1.4 to this system of characterisation.

It will be clear that the assessment of the complete reflection data of surface is a large job. Still, in the last 25 years, the complete data (or r-tables) as of many hundreds of road surface samples have been measured, notably in Denmark.
Unfortunately, it is very difficult to compare the results from different laboratories. In spite of that, several collections of reflection data have been published (e.g. de Boer (ed), 1967; Sørensen, 1975; Erbay, 1974; Burghout, 1977b, 1979).
Most of the research regarding the reflection properties of road surfaces relate to the dry condition and so do the systems to calculate luminance and to assess the quality aspects of road lighting. A noteworthty exception is the work carried out in Denmark under Frederiksen and Sørensen: the present Danish code for road lighting even includes a design system for wet surfaces (Frederiksen & Sørensen, 1976). Reference can also be made to relevant CIE-work (CIE, 1982b, 1979).

1.3. Quality criteria of road lighting installations

The great interest in the reflection properties of road surfaces results from the consideration that the luminance of the road surface is an important criterion of quality of a street lighting installation.
In the past, partly as a result of the impossibility to do otherwise, it was considered to be sufficient to determine the illuminance (the lux-value) of a road lighting installation in order to assess its quality.
Gradually the idea developed, however, that the illuminance gives very little information about the visibility to be expected in that particular road. It was realised that both the overall aspect of (and the level of visibility in) a particular lighting installation, that is with constant illuminance, could change quite dramatically when the road surface was changed, either when the street was resurfaced, or when the road became wet.
Furthermore, it was realised that the visual performance depends quite clearly on the level of adaptation, and that this level of adaptation is influenced to a large exent by the luminance of the road surface.
So gradually the illuminance has been replaced by the luminance as the primary criterion of quality for street lighting, and more specific as the quantity in which the level of lighting was expressed.
Finally the "luminance-technique" evolved, which means the methods of design and assessment which was closely related to the luminance concept.
As a consequence luminance, not quite correctly, did acquire the status of being fundamentally the final criterion with the much-recommended luminance value of 2 cd/m^2 (CIE, 1977).
Recently however, it is realised that the luminance is not the final word. The purpose of the road lighting is to "render visible" those objects that may endanger traffic. In this respect, the luminance concept is somewhat overrated. The illuminance, both on the road surface, and on planes perpendicular to it, are important. However, the luminance is likely to stay an important criterion for quality, not only the average value but also the pattern of luminance over the road, the so-called uniformity, and so will be the reflection properties of the road surface.
The luminance in existing road and street lighting installation can be measured. A survey is given by Schreuder (1967), see also Chapter 2.
Just as important, the luminance can be also calculated before the in-

stallation is made for design purposes. The most complete method is to calculate the luminance in a great number of grid-points on the road (e.g. 1 m apart across the road and 3 m apart lenghtwise). This can be done by directly applying the formula q = L/E. If q and the light distribution of the luminaires to be used is known, E and L can be calculated and thus for one lantern at the time. Adding the values gives L for the installation. This is repeated for all grid-points and using the individual L- values it is simple to calculate the average luminance and the uniformity.
This system is described in detail in the CIE-publication No. 30 (CIE, 1976). With modern computers the large bulk of required calculations is not a problem and the simplified methods proposed in the past are not required now.

1.4. Classification of road surfaces

The system proposed by Burghout (1977b) makes it possible to characterise a complete set of reflection data by just three well-chosen q-values (see 1.2.). As a figure of speech it is often said that in this way the road surface is characterised. This, however, is not particularly useful on its own. It is more important to know that the reflection characteristics of the surface can be identified in this way.
This means that this particular surface can be considered, for all means and purposes to be identical with that standard road surface, described in the standard catalogue, with the same numerical values of the reflection as measured in the three standard conditions. This identity is assessed by calculating the luminance and its distribution for the two surfaces (particular surface and standard surface) for a great number of lighting installation. When this is done on a large scale, it has been found that this identification process is valid (Burghout, 1977a).
The next step is to try and find a way to bring together road surfaces that are similar in groups. This classification turns out to be simpler than one might expect. Based on only two of the three characteristic reflection values it is possible to divide into groups all road surfaces included in catalogues such as those of the Danish Lighting Institute, Burghout or the Philips Lighting Laboratories. This division into groups implies that within each group there is only one surface (r-table) that

represents the whole group, in such a way that the differences in luminance and uniformity between the representative r-table and all other surfaces (or r-tables) within the group is less than some 5-10 per cent, for each of a great number of calculated lighting installations. This means therefore that this representative r-table really does represent all the individual r-tables of the group.

It has been found that when one compares the values of the luminance and the uniformity, that for practical purposes it is enough to have two groups. Burghout's proposal is to have two groups of road surfaces, one when the specular factor $S_1 \left[= \frac{r\,(0,\,2)}{r\,(0,\,0)} = \frac{r\,(0,\,2)}{q_p}\right]$ is smaller than 0.4 (class CI) and another when S_1 is at least equal to this value (class CII).

The standard reflection table of class CI, referred to as standard table CI is given in Table 1 as an example.

The S_1-value of the border between the classes is given in the Table 2 together with the normalised q_o-values and the specular factor S_1 of the standard tables.

In Section 1.5. we will come back to the question of whether this value of 0.4 has any further meaning. This Burghout proposal is accepted by the Subcommittee of the CIE dealing with road surfaces (CIE, 1982) and is now in the process of being established, in an official CIE Technical Report, as the official CIE recommendations making the present standards obsolete. This, by the way, has always been the aim of CIE: the present so-called R and N standards, which are described in CIE (1976, 1977), have been adopted only on a temporary basis.

All this is worked out mainly for dry surfaces, but there are proposals for a classification for wet road surfaces (CIE, 1979, 1982b).

1.5. The relation between reflection characteristics and other properties of road pavements in public lighting

The road surface is part of the traffic environment. In order to fulfil its purpose, it must meet a number of functional requirements. The so-called functional approach is explained in detail by Schreuder (1970, 1970a).

In order to drive safely on the surface, the skidding resistance, particularly in wet conditions, must be high and the light reflection should be as high as feasible, in order to ensure a clear picture of the road alignment. It should be realised, however, that when the road surface itself is very bright, the contrast between the surface and the horizontal markings can be unduly reduced. Furthermore, the road must ensure adequate drainage to reduce splash and spray (Welleman, 1976). For comfortable driving, the road must be even. For economic considerations, these functional requirements must be kept over a long period in time, ensuring a long service life of the surface.
There is, however, a close interrelationsship between the different functional requirements. First, the major obstacles for high skid resistance and high light reflection in wet conditions is the forming of pools so that drainage, smoothness of roadway and a coarse macrotexture are necessary in all cases. The only extra factor for the light reflection is that light-coloured aggregates are favoured, a requisite of no importance for the other functional requirements.
Summing up, the optimum road surfacing in view of the different functional requirements, is smooth, has good draining properties and a coarse top layer with light-coloured aggregate provided that there is sufficient contrast with road markings. Porous asphalt mixes are of interest because of their ability to drain water through the pavement. It is a matter of further research to develop a really optimal road surface having the advantages of light coloured top layers and porous asphalt mixes. Costs should be considered as well, but only on the basis of a cost-benefit analysis. In this analysis, the trade-off between the costs of more expensive light aggregates and reductions in the costs of lighting must be included (Phillips, 1976; Prevot, 1977; Decoene et al, 1984). It is not possible to give quantitative data that are generally applicable: for each specific case detailed economic studies should be undertaken.

The next question is to find out how this recommended "optimum" surface will fit in into the two-class system which has been accepted in principle by CIE. In this respect we will go back to the question whether the S_1 value of 0.4 had any special significance. On the basis of the available research it seems that this is the case indeed.

Although the number of road surfaces in the Burghout catalogue for which the composition is accurately known, is unfortunately fairly small, enough data is available to come to the following tentative conclusions (Burghout, 1982):

- all Portland cement concrete roads, and all bituminous roads with a sufficient amount of light-coloured aggregates fall within class CI (see Figure 3);
- all other conventional types of surfacing may either fall into class CII or CI.

Furthermore, nearly all the Portland cement concrete roads and most bituminous roads with more than some 15 to 30 per cent (depending on the degree of whiteness of the stones) of light-coloured aggregates ($\geqslant$2 mm) have a value of q_p $[= r(0, 0)]$ of 0.08 or more; this means that they will yield a high average road surface luminance under conditions of public lighting. The value of 0.08 for q_p is used as a criterion because it represents the average q_p value for all surfaces in the class for which $S_1 < 0.4$. $q_p > 0.08$ means therefore a surface that is "lighter than average". It should be noted that q_p is used as a norming factor. All individual luminances as calculated according to the adopted CIE method are directly proportional to q_p. This should not be confused with the fact that roads of class CI have a high luminance yield as a result of the favourable shape of their reflection indicatrix.

The work summarised very briefly in this Section has been performed mainly by Burghout under the auspices of the Working Committee "Road lighting and surface texture" of the Study Centre for Road Construction SCW (Netherlands). The final report of this Working Committee, which will contain all relevant details, will be published in the near future. This report will also contain more detailed data on the relationship between the road texture (macro-texture) on the one hand and the reflection and the skid resistance on the other hand. The relation with noise generation is discussed elsewhere.

With the aim of improving luminance and hence the visibility of bituminous surfacings and also to reduce energy expenditure on street lighting, some countries specify the use of light-coloured stones for

lighted roads:
- either through incorporation into the bituminous concrete, as for instance in Denmark (15 to 20 per cent of aggregates ⩾ 2 mm);
- or, in the form of chippings, as for instance in Belgium (6 kg/m^2 of 10/14 mm stones with a reflectometric value of at least 45 per cent (CRR, 1979; Decoene et al, 1984).
So as not to to compromise the contrast between the pavement and the road markings the authorities endeavour not to exceed the above rates.

1.6. Lighting with vehicle lights; Daylight conditions

1.6.1. Lighting with vehicle lights

In most industrialised countries urban roads, unlike most rural roads, are generally provided with street lighting.
In the specific case of detecting small obstacles the only obligation is to obtain a good contrast in the luminance of the obstacles and their immediate environment. To attain this end it is in principle enough to have vehicle lights of high luminous intensity if the pavement is dark. The obstacle will be visible as a light object against a dark ground. In practice this effect is obtained only if vehicles use their headlights and this is not the case when they dip their lights for oncoming traffic. More important is the fact that the detection of small objects is only a part of the driving task. It has been found, both from accident studies and from laboratory investigations that following the road may be just as important. This important sub-task is greatly simplified when the direction of the road is clearly visible. Thus, even with vehicle headlighting the road surface should be as bright as possible (Walraven, 1981), maintaining, however, a good contrast with markings and road edges.

A number of studies have included the lighting by means of vehicle headlights as illuminator. The studies by Burghout under auspices of SCW are reported in (SCW, 1979). More recently, a number of studies have been incorporated in the joint CIE - PIARC report (CIE, 1982b). The result is, of course, predictable as the same relationships with macrotexture (which is important from the point of view of retroreflection), evenness, drainage and lightness are favourable for both vehicle lighting and public lighting.

1.6.2. Daylight

Daylight seems to have less problems. The lighting conditions are different, but not radically different from those of public lighting, thus one should expect that the reflective properties can be described by similar parameters. Indeed, this is the case with q_o being the most important parameter (CIE, 1982b; Mader, 1968).
A separate problem is the luminance that may become too high for comfort in direct sunshine. Because this discomfort can be easily counteracted by wearing sun glasses it seems that, using the cost-effectiveness point of view, this aspect should receive little emphasis.

Two more aspects related to the daytime situation should be mentioned. First the wet condition where the problems of excessive reflection can be counteracted by the same measures as were relevant for the night situation. This is obvious because they have the same purpose, that is getting rid of the water film on the road. It is clear from the fact that we come back to it over and over again, that the wet condition of the road is a very important and dangerous situation. A number of OECD working groups have studied this matter in detail and we may refer to the reports of these groups for further details (CIE, 1982b; OECD, 1976a, 1976b, 1980). The second remark is related to the excessive glare that may result from a low sun, again particularly when the road is wet. Again it is the same set of countermeasures that may reduce this glare.

1.7. Road markings

In the foregoing we have indicated that, according to modern opinion and insight, keeping the vehicle on the road is much more important, both as an accident factor and as a sub-task of handling the vehicle, than avoiding small obstacles. It follows then that road markings deserve much attention, much more maybe than they did receive in the past. Now road markings have been studied in detail by a separate OECD group (see OECD, 1975), so it may be not necessary to discuss these in detail. However, particularly the emphasis placed on porous, light coloured road surfaces may present some special problems.
There exists a large variety in road markings, both as regards materials

and application. We will concentrate here on the more conventional types, that is the "horizontal markings" (paint, hot applied and cold applied plastic) and "raised pavement markers" (road studs, usually with retro-reflecting elements). The delineators are of less importance here, as they do not interfere with the road surface.

New road paints follow the texture of the surface. They do not, therefore interfere with the drainage of the road; on the other hand, when the paint and the adjoining road is covered with a film of water, the difference in reflection disappears. This means that road paints are invisible on a wet road surface. This is true for all (three) different types of illumination: daylight, public lighting and vehicle lighting. Adding glass beads to the paint enhances the retro-reflecting properties of the marking quite dramatically in the dry condition, but it does not help at all when wet, because the beads are covered as well by the water film; they are thus rendered useless. Another point is that painted markings have a very short life span; they are not recommended for road marking particulary for axial marking in important roads.

Plastic road markings - either hot applied or cold applied - form a layer of several millimeters thick. On conventional road surfaces, they may interfere therefore quite seriously with the drainage properties of the road surface, and they may cause quite large pools of water above them. This is a problem for side markings and also for lane markings on multi-lane roads. One quite effective countermeasure is to apply the material in such a way that small drainage openings are left free. An example is the profiled (or corrugated) road marking (See Schreuder, 1981).

The visibility of the road marking depends upon the contrast between marking and road. Usually, when dry, the contrast for plastic materials is acceptable, although less than for paints. Again here, adding glass beads is a great improvement for vehicle lighting condition. In wet condition the situation is often still acceptable for daylight and public lighting conditions because the difference in texture between the marking and the road renders the marking visible in spite of the fact that the luminance contrast may be quite small as the result of the water film. However, in vehicle lighting conditions the markings are, when wet, again practically invisible - even if they are provided with glass beads.

An acceptable level of visibility can be arrived only if the marking presents near-vertical planes so that the light can enter into the glass beads, vertical planes high enough to protrude over the film of water. Again in this respect the profiled markings prove to be very effective; another solution is to supplement the lines with raised pavement markers (Tooke & Hurst, 1975).

Raised pavement markers, particularly those equiped with retro-reflectors of the corner-cube type can be quite effective under vehicle lighting conditions, both dry and wet. Apart from the price, they have two disadvantages: they are poorly visible in daytime, particularly when dry, and it is difficult to approach a "line" in the juridical seuse. On the other hand, the often-mentioned disadvantages related to motorcycle riding and snowplowing seem to be neglegible. Combining all these factors, it seems that an optimal solution can be found by applying thermoplastic profiled markings in combination with raised pavement markers for road markings on important roads.

In some cases e.g. side markings and markings of minor roads, reflectorised road paint may be used.

The subject of road markings and particularly their wet night visibility is dealt with in detail in Tooke & Hurst (1975), Blaauw & Padmos (1982) and Schreuder (1980).

2. MEASUREMENT OF REFLECTION PROPERTIES

2.1. Photodetecors

Measuring the optical characteristics of road surfaces is a branch of photometry. For photometry in general we refer to the outstanding classical works (Walsh, 1953; Kertz, 1967; CIE, 1982).
In the past, all photometry was visual. The principle was to compare two adjoining areas with different brightness, or to adjust the one in such a way that it equals the other. Essentially, it is an assessment of brightness. If one of the two areas is calibrated in terms of luminance (see footnote in para. 1.1.) the photometry is a luminance measurement.
However, visual (subjective) photometry became obsolete. Now all modern photometry is based on objective measurement of light, light quanta or photons. A number of photoreceptors are available, but for practical measurements in photometry, and particularly in street lighting photometry, only two are applicable: the barrier-layer photocells and the photomultipliers.

1. Barrier-layer photocells. A semi-conducting layer between two conductors may yield a (photo)voltaic difference between the conductors proportional to the amount of light (the number of photons) striking the surface. This can be converted in a photocurrent. When the dimensions are selected in an appropriate way, the photocurrent is proportional to the light level, the illuminance on the cell in this case, and can be measured by means of a micro-amperemeter. This is the way the current "Luxmeters" are constructed.
Their advantage is their simplicity as simply a cell and a micro-amperemeter are sufficient and no additional source of energy is required. Provided the sensitivity to different colours is adjusted to the human eye, or rather to the international regulations, barrier-layer photocells can be extremely sensitive, reliable and accurate. They are the standard equipment in all photometric laboratories.
Originally, the barrier-layer was made out of selenium. More recently, the even more relaible and accurate silicium-cells are in common use.

2. Photomultipliers. Here, a completely different physical principle is applied. When light strikes a metal, the impact of the individual photons knocks electrons out of the metal surface. When in vacuum a voltage difference is applied to the metal, the electrons are sucked away and may form an electric current, again proportional to the amount of light striking the metal, in this case called the photocathode. In a simple photocell the electrons are collected by the anode. However, it is possible to arrange another metal surface in the way of the electrons (a dynode) so that each oncoming electron that strikes the metal, will knock out several "secondary" electrons. This process can be repeated (e.g. ten times in current photomultipliers) so that for each incoming photon the end result is a cascade of (secondary) electrons, forming a quite considerable photocurrent.
The result is a highly sensitive instrument. In fact, photomultipliers were originally developed to count individual photons. Their disadvantage is that they require a rather complicated gear, such as highly stable/-1000 V anode voltage. Photomultipliers are indispensable for accurate measurements at low light levels but they require specialist operators. This severely restricts their application.
Details of the measuring equipment and their operation in road lighting are given by Schreuder (1967). An up-to-date survey of the area of photon-detectors is given in the symposium of the same name (IMEKO, 1982).

2.2. Measurement of reflection characteristics

2.2.1. General

The reflection of a (road) surface can be characterised by the luminance factor $q = L/E$ (see 1.1.). This definition suggests a measuring method: simply measure L and E under the appropriate geometry, and q can be calculated. This is precisely what is done in practice, either by direct measurement or by means of a comparison with a calibration standard. The different aspects of these type of measurements are discussed in great detail in a forthcoming report of CIE and PIARC (CIE, 1982b) on which the following summary is based.

2.2.2. Samples of road surfaces

The surface to be measured should be representative of its normal state. This means that it should not be less than about one year old, as the reflection characteristics change markedly during the first few months of wear, while after that they are expected only to vary with the seasons. Little is known about the magnitude of this effect on reflection characteristics, but it is wise to avoid sampling a surface after a period of unusual weather.

There may be considerable variation in reflection properties across the width of the road, due to wheel tracking. Several measurements should be made, or a careful choice made of a typical site. If there is doubt about the position to be sampled, it si recommended that positions be chosen to represent wheel-tracks, between tracks and near the gutter and crown of the road.
The site or sample should be chosen while viewing under the type of lighting deemed to be relevant, that is, daylight, street lighting or headlighting or perhaps all three. Patches or surface changes sometimes invisible under daylight conditions, particularly when the surface is wet, but become obvious under street lighting.

2.2.3. Measuring equipment

The set-up consists of three main components, the road surface or the road sample, an illumination system including a light source and an optical system, and finally a luminance meter, including a photo-electric detector and an optical system. It is assumed, that the optical system of the luminance meter defines a measuring field, that is contained within the illuminated field which is itself defined optically or geometrically by the size of the equipment or the sample.

In principle there are two types of optical systems for the luminance meter. Both use the same components, but of different dimensions and for different purposes.
Beginning from the road sample moving towards the detector the components are, a front mask, a lens, a rear mask, and a detector. The two types of

luminance meter are called the focussed system and the unfocussed system. The focussed system is like a common tele-photometer. The front mask is the entrance pupil of the lens (usually circular) and determines the aperture angles of the system. The lens is of a relatively short focal length and forms an image of the sample on the rear mask. The rear mask (or field stop) then serves to limit the measured area. The detector is behind this rear mask, possibly focussed on the main lens by applying a small field lens. See Figure 4.

The unfocussed system is rather like a telescope focussed on infinity. The front mask is narrow and wide as its purpose is to determine the measuring field. The lens is of relatively long focal length and has the rear mask at its principal focal point. This means that the rear mask appears infinitely distant as seen from the sample, and is used to determine the aperture angles by its angular size as seen from the lens. The detector is close behind the rear mask. See Figure 5.

In use the two systems may be compared in terms of working distance, sharpness of edges on the measured area, and maintenance of angle of view. The working distance of the focussed system is relatively large in order to minimise both the aperture angles and the variation of angle of view across the sample. The edges of the measured area are quite sharp. The working distance of the unfocussed system is as small as possible to minimise the hazy edges of the measured area. The angle of view is the same from all parts of the sample, as the rear mask is optically infinitely distant.

In principle the illumination system can also be of the focussed or unfocussed type, the focussed system being like a slide projector and the unfocussed system, a collimator.

So far, there is no distinction between measurements in the laboratory and in situ, for which a few special considerations are given later.

2.2.4. Alignment

For the measurements the equipment is placed on the road surface or the sample is placed in the equipment in such a manner that the upper parts of the texture of the surface lie in the reference plane.

This implies that the surface or sample itself should define a plane to a sufficient accuracy, so that the measuring angles can be set properly. The surface or sample must not be curved and must also have dimensions which are large compared to typical heights in the surface texture.
The CIE report gives a number of valuable hints as how to arrive at an accurate alignment (CIE, 1982b).

2.2.5. The measuring and illuminated fields

The measuring field should be large enough to contain a significant number of stones or chippings of the surface. This depends on the type of surface and the size of stones and chippings. Further, it should be taken into account that at low angles of illumination and observation some stones are in the shadow or hidden behind others, so that the number of stones in the measuring field is effectively reduced.
A measuring field of at least 100 cm^2 may be considered to be sufficiently large. When the measuring field is smaller than this, a sufficiently large measuring field can be achieved by repeated measurements on different positions on the surface or sample.
The measuring field should receive uniform illumination with a shadow formation corresponding to the real road surface. This means that the illuminated field should include reserve areas in the front and back of the measuring field.
The required length of the reserves will depend both on the texture of the surface and on the angles of illumination. The required length of the reserves cannot be specified.

2.2.6. Measurements on samples

It is convenient to use a large room for the measurements, so that the required measuring angles can be easily arrrived at without obstructions from the luminance meter and the illumination system. A large room allows the use of the relatively simple focussed system for the measurement.
If necessary, the overall dimension of the equipment can be reduced by deflecting either the incident or the reflected light by means of mirrors or prisms. Obviously this implicates the set-up and adds to the sources of possible errors. Also the unfocussed measuring system can be used.

The advantages of measuring on samples in the laboratory are obvious if compared with in situ measurements.

For street lighting conditions a sample of 100 cm^2 is large enough. Samples of 20 cm x 40 cm as recommended in CIE-publication No. 30 (CIE, 1976) are also adequate for the measurement of the luminance coefficient for headlight illumination. The sample should be measured as soon as possible after removal from the road, as changes may occur in laboratory storage conditions.

An average "standard wet condition" may be approximated in laboratory measurements by wetting at 5 mm per hour until draining is stabilised and measuring 30 minutes after switching off the water, in a room with an air temperature of 25^o C and humidity 50 per cent.

2.2.7. Measurements in situ

For a portable equipment a number of practical considerations apply. The equipment should be sturdy, independent of the mains and of such dimensions and weight as to be easily portable. For measurements with regard to street lighting the equipment must also allow a large variety of directions of illumination.
Further, the equipment should have screenings to eliminate the effect of stray light so as to allow its use in daytime.
When stabilised power is not available and because long warm-up periods are undesirable, the equipment should have facilities for an easy secondary calibration for variations in illumination and in sensitivity of the luminance meter.
Since a limitation of the dimensions of the equipment is important, it is usually necessary to deflect both the path of the incident light and of the reflected light. This can be done by means of mirrors or prisms.

In order to have small dimensions and simultaneously a sufficiently large measuring field, a luminance meter of the unfocussed type is probably advantageous. One disadvantage of this system is, however, that the size of the lenses do not permit directions of illumination close to the direction of observation, unless the two are mixed in a semi-transparent mirror or by other means.

If the "standard wet condition" is defined as that wetness exceeded only 10 per cent of the time, then this will obviously vary with the seasons, depending not only on the road surface, but also on the local weather. This means that it is very difficult to achieve accurary for measurements in situ.

2.2.8. Angles of illumination and observation

The geometry upon which the luminance coefficient of a road surface depends is given in Figure 1.
The angle of observation α is fixed at 1 degree for measurements. The measuring results obtained are valid within the range of α-values from 0.5 to 1.5 degrees, which covers the important part of the road in practice. The viewing direction is taken parallel to the road axis and direction of traffic.
Measurements for headlight as illuminator introduce the special feature that angles of illumination are even smaller than the angles of observation. This feature calls for a number of special considerations, which are discussed in detail in the CIE report (CIE, 1982b).

2.2.9. Aperture angle, recommended set-up

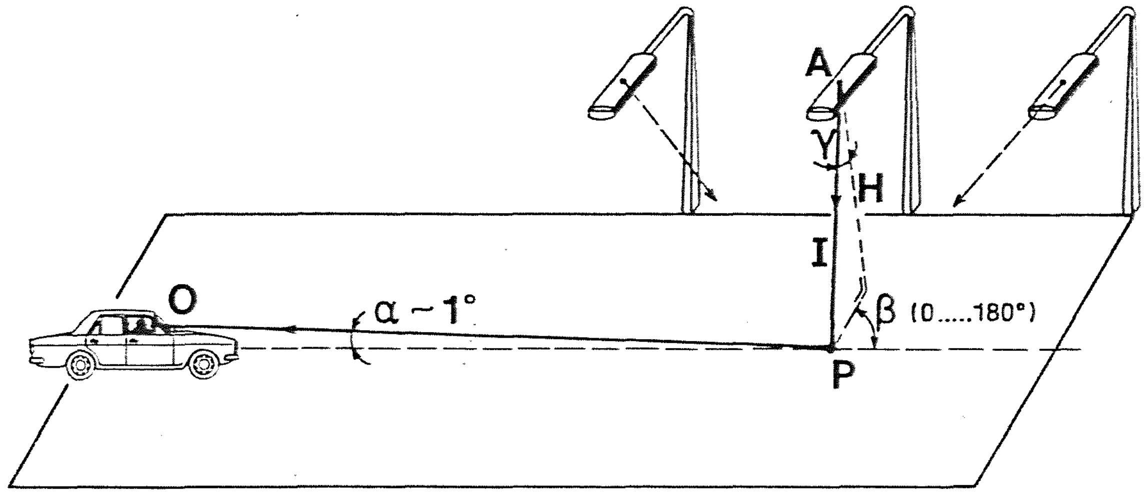
Aperture angles have an influence upon the measured shape of the angular distribution of the luminance coefficient especially when the values vary strongly with the angle of light incidence, for example in the vicinity of specular reflection. Therefore a certain set-up for the illuminant is recommended. As shown in Figure 6, the light source should be moved along a straight line at a constant height above the sample. The solid angle subtended by the light source will therefore decrease with increasing angle of incidence, γ, thus to a certain extent simulting the practical conditions found in road lighting installations.

Methods using a constant distance between light source and sample for all angles of light incidence, γ, may be more difficult, especially for specular surfaces. In this method the solid angle, subtended at the field of measurement, is kept constant, and a smoothing of the reflection indicatrix may occur. It should be realised that in this part of the r-table, values are separated by only 2 degrees in azimuth and less than one-quarter of a degree in elevation. The aperture angle of the luminance meter has to be kept small. Investigations show that a maximum of 5' int the vertical and 10' in the horizontal plane are satisfactory.

In the situation where the road is illuminated by the drivers own headlights (β close to 180), the influence of the angle β is considered to be small. Thus a very accurate setting is not required and fairly large aperture angles in the horizontal direction for both the illumination system and the luminance meter are permissible. A maximum aperture angle of 0.33 degrees in the horizontal direction is suggested. In the above mentioned situation the signal is not expected to vary rapidly with the angle of measurement and, therefore, the apeture angles in the vertical direction do not have to be very small either. Values up to say 10 per cent of the measuring angles themselves could be considered to realise adequate accuracy. It is to base the equipment on the focussed system and to use large measuring distances. Often, and in particular in portable equipment, mirrors are introduced in order to reduce dimensions. Whenever mirrors, lenses or other optical devices are included in the paths of illumination and observation, scattered light introduces a false measuring signal, which must be subtracted from the total measuring signal.

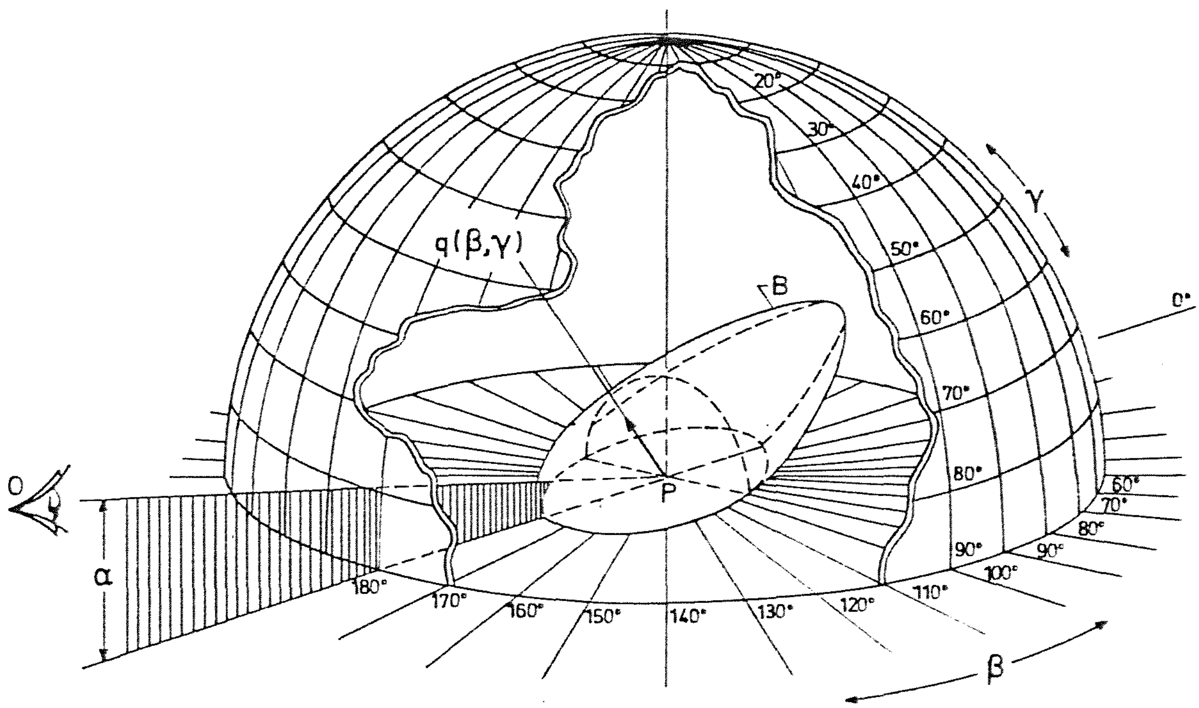
One final remark. In the past, great emphasis has been placed on a classification system of road surface reflection-characterstics based on the average luminance factor q_o. A number of ingenious measuring systems for q_o have been designed (Schreuder, 1967). However, as described earlier, the classification system itself was not quite satisfactory, and it has been replaced in the mean time by the two-parameter system proposed by Burghout (1977b). This two-parameter system requires only a small number of measurements of q in very specific geometry, which can be executed simply - by means of the equipment explained above - in the laboratory at least. The in situ measurements are still a difficult problem, that is not solved completely. A number of the considerations for in situ measurements are described in detail by Helms (1982).

FIGURES AND TABLES



α = angle of observation
β = angle between vertical plane of incidence and vertical plane of observation
γ = angle of incidence

Figure 1. Angles upon which the luminance-coefficient is independent.



The luminance coefficient q corresponding to the observation position O and a direction of incidence of the light (β, γ) is indicated by a line segment in the direction (β, γ) whose length is proportional to the luminance coefficient. The end points of these lines describe the surface of the indicatrix B.

Figure 2. The luminance-coefficient indicatrix (After Schreuder, 1967).

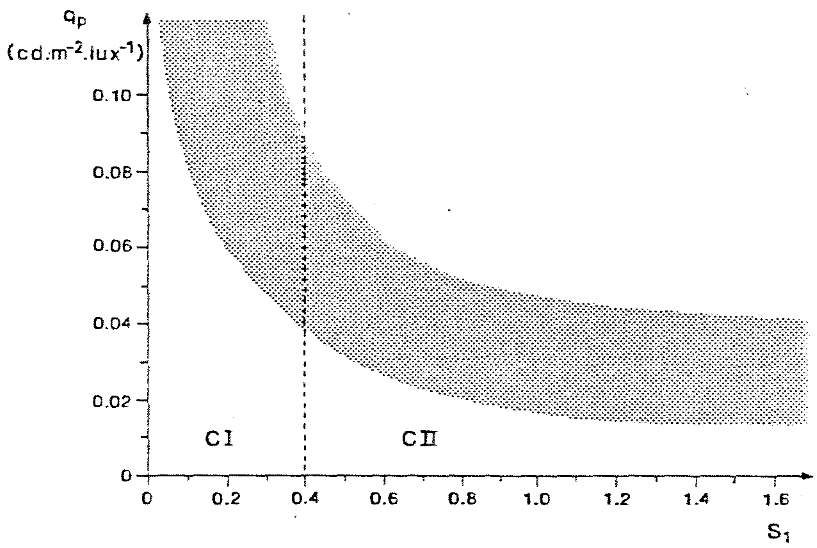


Figure 3. Relationship between q_p and S_1 for dry road surfaces (Normal bituminous concrete of various design, bituminous concrete with light-coloured aggregates, cement concrete) (After SCW, in preparation).

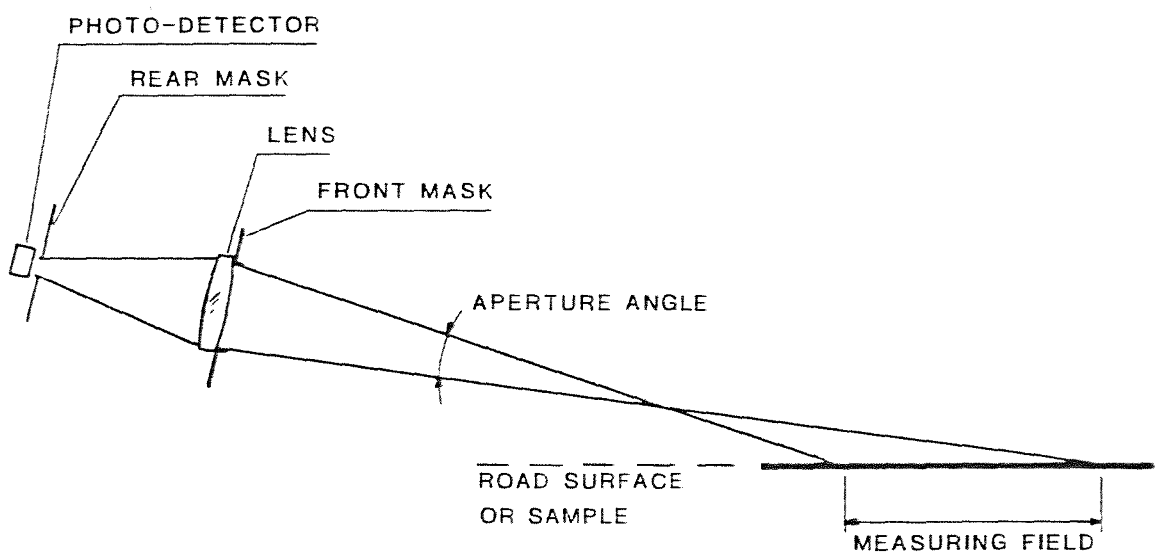


Figure 4. Principle of the focussed luminance meter.

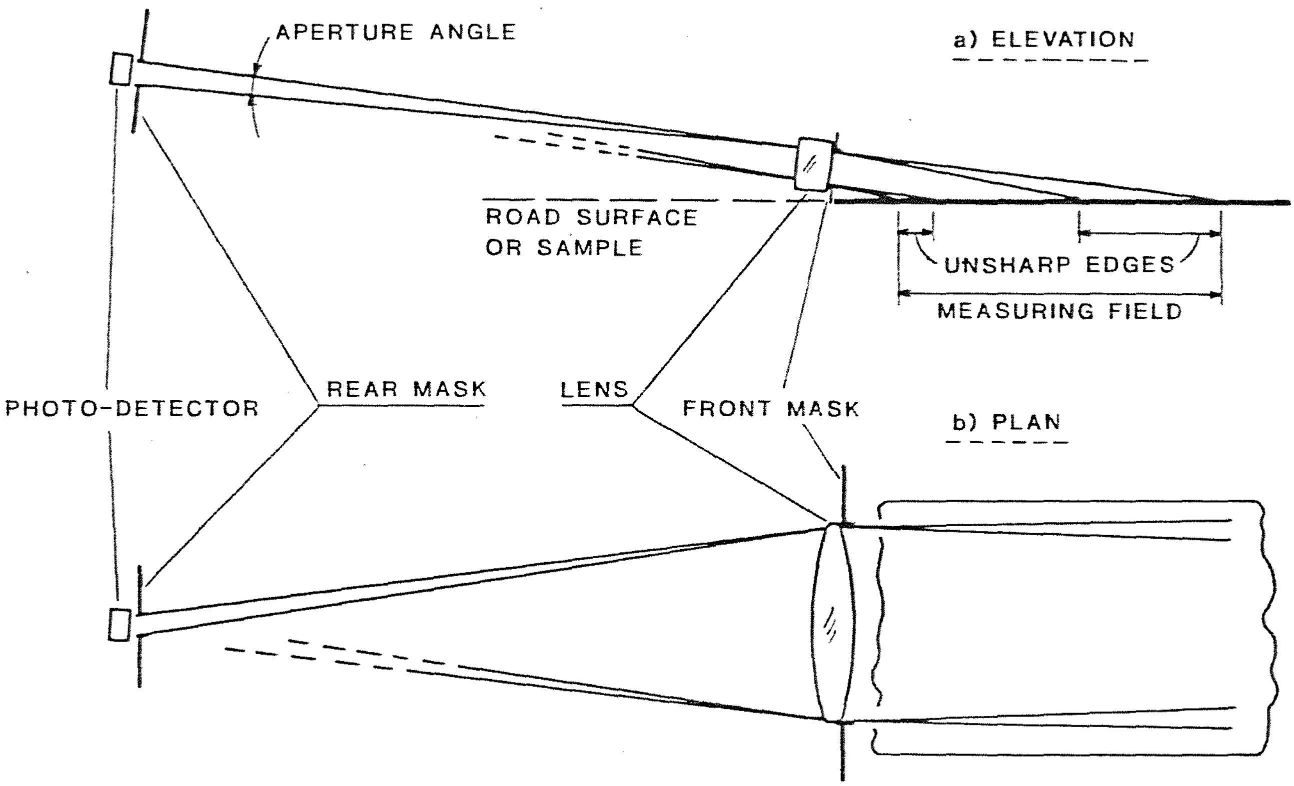


Figure 5. Principle of the unfocussed luminance meter.

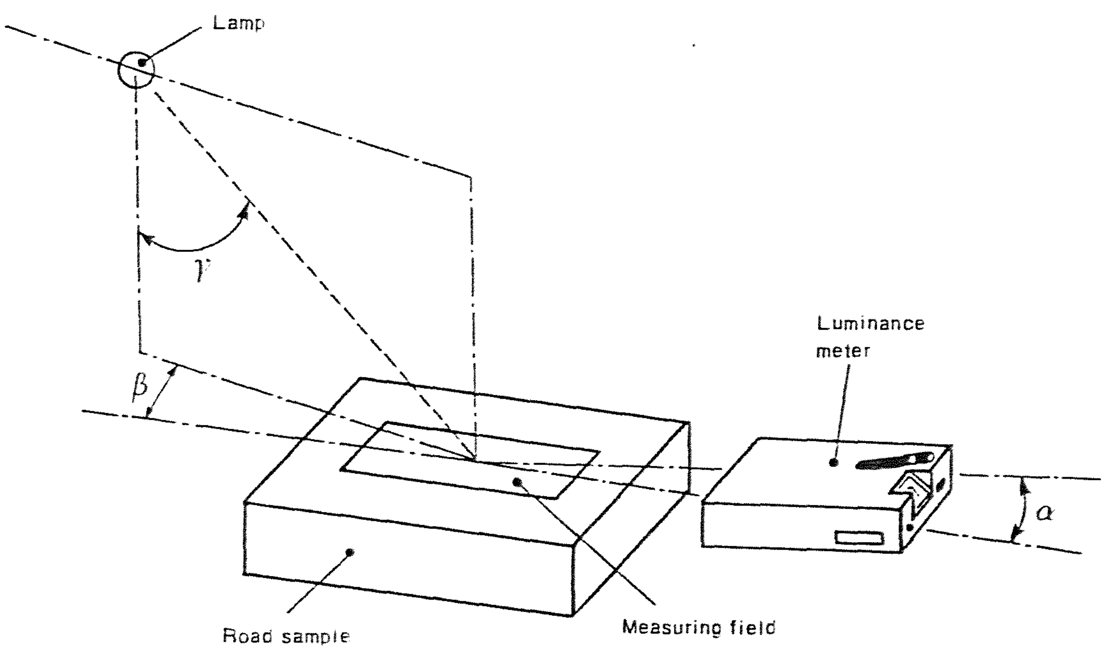


Figure 6. Principle of the recommended equipment.

tan gamma \ beta	0	2	5	10	15	20	25	30	35	40	45	60	75	90	105	120	135	150	165	180
0	770	770	770	770	770	770	770	770	770	770	770	770	770	770	770	770	770	770	770	770
0.25	710	708	703	710	712	710	708	708	707	704	702	708	698	702	704	714	708	724	719	723
0.5	586	582	587	581	581	576	570	567	564	556	548	541	531	544	546	562	566	587	581	589
0.75	468	467	465	455	457	446	430	420	410	399	390	383	373	384	891	412	419	437	438	445
1	378	372	373	363	347	331	314	299	285	273	263	260	250	265	278	295	305	318	323	329
1.25	308	304	305	285	270	244	218	203	193	185	179	173	173	183	194	207	224	237	238	245
1.5	258	254	251	229	203	178	157	143	134	128	124	120	120	132	140	115	163	177	179	184
1.75	217	214	205	182	153	129	110	100	95	90	87	84	88	98	103	116	123	134	137	138
2	188	181	174	142	116	95	80	73	69	64	62	64	64	72	78	88	95	105	108	109
2.5	145	136	121	90	66	53	46	41	39	37	36	36	39	44	50	55	60	66	69	71
3	118	108	87	57	41	32	28	26	25	23	22	23	26	28	31	37	41	45	47	51
3.5	97	87	64	39	26	20	18	17	16	15	15	16	17	19	23	27	30	33	35	37
4	80	69	50	29	17	14	13	12	11	11	11	11	13	15	17	19	22	26	27	29
4.5	70	58	37	21	13	10	9	8	8	8	8	9	10	12	14	16	17	20	21	22
5	60	51	29	15	9	7	7	6	6	6	6	7	7	9	10	12	14	17	17	18
5.5	52	41	23	12	7	6	6	6	5	4										
6	48	36	19	8	6	5	5	5	5											
6.5	44	32	17	7	6	5	5	5												
7	41	28	14	6	5	4	4	4												
7.5	37	26	12	6	4	3	3													
8	34	23	11	5	4	3	3													
8.5	32	21	9	5	4	3	3													
9	29	19	8	4	3	3														
9.5	27	17	7	4	3	3														
10	26	16	6	3	3	3														
10.5	25	16	6	3	2	1														
11	23	15	6	3	2	1														
11.5	22	14	6	3	2															
12	21	14	5	3	2															

Standard reflection table Cl

class CI

$q_o = 0.10$

Table 1. Standard r-table of class CI.

Class	Standard table	S_1-limit	S_1 of standard	Normalised q_o value
C I	C 1	$S_1 < 0.4$	0.24	0.10
C II	C 2	$S_1 \geq 0.4$	0.97	0.07

Table 2. Standard classification system.

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