# VISUAL PERCEPTION AND DAYTIME RUNNING LIGHTS (DRL)

## A literature study

R-90-43

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Leidschendam, 1990

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## SUMMARY

As part of the discussion on whether daytime running lights (DRL) should be introduced in the Netherlands as a rule of conduct, arguments - pro and con - often relate to visual perception. Vehicles would be more conspicuous as a result of DRL, would be detected sooner and/or be better recognised, the distance to other vehicles could be better estimated, etc. On the other hand, it is also suggested that lighting in the daytime or during twilight may lead to glare, or that road users not using lights (e.g. cyclists and pedestrians) would become less conspicuous as a result of DRL.

Central to this report is the question of when 'positive' and 'negative' effects (relevant to visual perception) may be expected with DRL. In order to understand the relationship between both types of effects, one model is presented in which all types of studies (both detection experiments and studies on glare, for example) are included. The model is primarily intended as a conceptual framework; it has proven useful for describing various types of study in relation to each other.

In general, it can be said that the higher the adaptation luminance (largely determined by the illuminance level of the surroundings), the greater the luminous intensity (of DRL lamps) should be to realise further 'improvement' - in terms of detection, gap acceptance or assessment of visibility, for example - with respect to a situation without lighting and the greater the light intensity can be before it will give rise to any glare. As a result, whatever light intensity is chosen, there will always be a 'grey area' between 'desirable improvement' and 'undesirable glare'. Under 'conditions of daylight' (> 100 to 200 cd/m$^2$) at a luminous intensity of 1000 cd, for example, there will virtually never be any risk of glare while improvement in visual performance can certainly be expected. In the twilight period however, a luminous intensity of 1000 cd can lead to signs of glare. If a lower luminous intensity (e.g. 400 cd) is chosen to compensate for this phenomenon, it will be unable to offer any 'improvement' under very bright lighting conditions.

Subsequent studies should weigh up the need to avoid glare and the need to improve visual performance, in order to arrive at an 'optimal' choice for

the luminous intensity of DRL lamps. This requires studies that are more comparable to 'true traffic conditions' than most studies conducted to date. In addition to visual perception aspects, attention will also need to be directed towards more cognitive processes, decision-making and ultimately behaviour in traffic, since an improvement in visual performance does not necessarily imply safer behaviour.

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## FOREWORD

The present report offers a literature study dealing with "visual perception and daytime running lights (DRL)". In recent years, much discussion has focused on the issue of whether DRL should be introduced into the Netherlands as a rule of conduct. Arguments for and against were often proposed in relation to visual perception. One of the arguments expressed against DRL concerns the assumption that DRL would lead to glare. The Department of Road Transport (RDW) of the Ministry of Transport was interested what was actually meant by the term 'glare', when this phenomenon was present and whether there would indeed be question of glare with the introduction of DRL. As part of ongoing research into the possible effects of DRL on traffic safety SWOV is conducting on behalf of the Transportation and Traffic Research Division (DVK) of Rijkswaterstaat, the Department of Road Transport (RDW) has asked SWOV to conduct a literature study in order to obtain some insight into problems of glare.
In the discussions surrounding DRL, the subject of glare is only one of many associated with visual perception, and can be better understood when other aspects of visual perception are also considered. Therefore, this literature study does not treat the subject of glare as a separate entity, but places it in a broader context.

# 1. INTRODUCTION

Various accident studies conducted overseas report a drop in the number of accidents as a result of the use of daytime running lights (DRL). These studies have given rise to some dispute, usually based on methodological and statistical considerations. It is therefore of great importance to understand the actual effect of DRL: on which mechanisms of effect is DRL based? How does DRL influence visual perception?

The greatest problem when determining the effect of any measure on visual performance or assessments (in terms of detection, visibility, conspicuity etc.) is that the relationship between such indirect measures and behaviour and accidents, for example, has not been sufficiently documented. An improvement in 'visibility' does not necessarily mean that driver behaviour will change. Nevertheless, it is worthwhile investigating these 'perceptual aspects'. Effects in terms of accidents can be better understood if the preceding processes are also considered. Insight into the underlying factors that could explain the effect of DRL - whether in a positive or negative sense - also allow the assessment of specific hypotheses in future accident studies.

When we consider the various stages of information-processing, i.e. perception - evaluation - decision-making - action, it will be clear that if something goes wrong at an early stage (e.g. perception), subsequent steps will be affected. It hardly needs saying that the majority of information used by a traffic participant is visual in nature. 'Not seeing' a certain object is of crucial importance, as a mistake at this early stage will handicap each subsequent process - such as recognition, decision-making and action - not to speak of obstructing it altogether.

Lighting on vehicles play a twofold role with regard to perception: it is important for "seeing" and "being seen". In general, vehicle lighting is related to both how the vehicle is seen by others and how the vehicle illuminates its surroundings. One characteristic of DRL is that its function is not so much to light its surroundings (as would be the case at night), allowing the driver of the vehicle to 'see' properly, but to allow the vehicle to be 'better seen' by others (compared to the vehicle not using lights) (e.g. see OECD, 1990, pp. 53-54). DRL will therefore be used mainly to make the vehicle more "visible" to others.

What could DRL add to the visual information that is already reaching us in traffic? Arguments relating to 'conspicuity' and 'detectability' etc. are often put forward. DRL could help to make vehicles more conspicuous, they could be detected sooner, they would be recognised sooner and/or better, the distance to other vehicles would be more accurately estimated, etc. The likely influence DRL would have on visibility, detection, conspicuity, recognition and identification will be discussed in this report.
In addition, speculations are expressed from time to time concerning the negative side effects of DRL: lighting in the daytime or during twilight may cause glare, while road users without lights (e.g. cyclists and pedestrians) would become less conspicuous as a result of DRL. These aspects will also be discussed in this report.

The key issue in this report is therefore to consider the effects of DRL on various aspects of visual perception: when do 'positive' and when do 'negative' effects appear? In order to understand both types of effect, one model is presented in which all types of study (e.g. both detection experiments and studies on glare) are included. Results of the studies are discussed in this report and brought into relationship with the model as referred to in the above.

The report closes with conclusions and recommendations for further study. Finally, the appendix offers further insight into some concepts relevant to "light": what is light, how are various aspects of light and perception measured, etc.?

## 2. VISUAL PERCEPTION

Visual perception is a concept which refers to all perceptual processes and results imaginable. As a result of its generalised nature, the literature often distinguishes between the various aspects of perception. Concepts such as detection, conspicuity and visibility are often mentioned in the 'perception literature'. For the purposes of clarification, therefore, some of these concepts will now be discussed in brief.

### 2.1. Visibility and detection

The concepts of "visibility" and "detectability" are often interchanged. Visibility can be defined as a 50% probability of detection (threshold of visibility). If an object becomes 'more visible', it is generally implied that its detection 'improves' in one way or another, so that the probability of detection becomes increasingly greater (and therefore greater than the 50% already cited, at least); this implies that, in general, an object can be detected at a greater distance, or that observers need less time to decide whether or not an object is present (reaction time).

Visibility is subject to a human assessment component, as there is no equipment that can directly measure "visibility": human intervention is always necessary to determine this parameter. Often, such factors are studied with the aid of detection experiments. One important factor which determines whether an object is detected is the contrast between object and background. The contrast (C) between an object and its background is defined as:

$$C = (L_b - L_o) / L_b$$

with $L_b$ = luminance of the background

$L_o$ = luminance of the object.

This is generally expressed as a % (above expression * 100).

Although contrast is related to visibility, it is not the same thing. Di Laura (1978, quoted in Sanders & McCormick, 1987) offers a simple example of this phenomenon. Take an object which contrasts 50% with the background and illuminate it with a pocket flashlight on a large stage in a theatre: it will hardly be visible. Now take that same object, lit up by a large floodlight measuring 10,000 times the luminous intensity of the flashlight. The contrast remains the same, but the "visibility" differs markedly. Both luminance and contrast are important for visibility. Another factor is the size of the object; a large object on stage is more visible than a small one.

The degree to which the visual system is sensitive to contrast is therefore not the same under all circumstances. Blackwell (1946, 1968, a.o.) has probably conducted the most extensive research into the sensitivity of the visual system. For example, the lower the luminance level, the greater the contrast between an object and its background should be in order to ensure the same probability of detection. But given a particular luminance, the detectability of an object will improve if the contrast with the background is enhanced or if the object is larger, for example.

In order to measure the visibility of a particular object, it can be compared against a particular standard. Blackwell (e.g. 1968) has conducted detailed research into this aspect and has formulated a standard target: a luminous disc, measuring 4 arc minutes (approx. 0.07°) and presented in pulses of 1/5 of a second on a uniform screen having a given level of luminance. The task of the test subject was to detect the presence of the disc. In this way, Blackwell wished to determine the 'visibility threshold' of a standard target: the point at which the test subject could detect the disc in 50% of circumstances when it was presented. This method is suitable for determining the response of the visual system to small objects that are only just visible, but it is doubtful whether it says anything about how people "see" more complex situations. In addition, this method does not relate to supra- threshold perception, nor to perception which occurs not so much centrally (straight ahead) as peripherally (Sanders & McCormick, 1987).

## 2.2. Visibility and conspicuity

Sometimes "visibility" means more than simply "detecting something". One can detect "something" amongst other elements; in that case, one can speak of conspicuity. Or "something" may be recognised and identified as 'a car', for example (whether or not it is situated between other elements). In other words, "seeing" has various levels: with detection, the issue is whether an observer has decided that he has seen "something"; with recognition, he must also decide whether that something is recognisable; with identification, he must decide what exactly he has seen. The terms 'visibility' and 'conspicuity' are often interchanged in the literature.

Visibility does not necessarily imply conspicuity; a particular object may also be visible between similar objects (i.e. be detectable), but may not necessarily be conspicuous. According to Engel (1976, p. 87), visual conspicuity is defined as the "object factor, or more precisely, as the set of object factors (physical properties) determining the probability that a visible object will be noticed against its background".

Cole & Jenkins (1980; quoted in Cole & Hughes, 1990) define conspicuity as follows: A conspicuous object is an object which, for a given background, can be seen with certainty within an extremely short period of time, regardless of the location of the object in relation to the direction of view at the moment of fixation. According to Cole & Jenkins, this "extremely short period of time" is considered to be less than 200 msec, as it is impossible for eye movements to occur in that period of time. Eccentricity, i.e. the angle between the object and the direction of view, is an important factor in conspicuity (Cole & Hughes, 1984; Engel, 1976). The contrast between object and background and the complexity of that background is also important. Surprisingly, the size of the object did not play a dominant role.

Therefore, conspicuity in any case implies that a particular object must 'compete' with other objects in order to "attract attention", while visibility implies the detection of the presence of a particular object against an 'empty' background.

There are many 'definitions' (not all of them as clear) that describe the term 'conspicuity'. Wertheim (1986) and Theeuwes (1989) have offered an overview of these definitions. The measurement and definition of conspicuity is performed in so many different ways that it is in fact impossible to speak of 'the' conspicuity of an object. However, all definitions of conspicuity do share a reference to 'attention': a conspicuous object draws attention to itself (for example, see Theeuwes, 1989, p. 14). All definitions also state that external, physical factors determine the conspicuity of an object.

Nevertheless, factors other than external ones can influence conspicuity. Engel (1976) makes a specific distinction between visual conspicuity (bottom-up) and cognitive conspicuity (top-down). In more or less the same manner, Hughes & Cole (1984) have pointed out that conspicuity cannot only be regarded as characteristic of an object, precisely because it has to do with attracting attention. Whether an object will attract the attention of an observer is largely determined by that observer. Hughes & Cole therefore distinguish between two types of conspicuity: 'attention conspicuity' and 'search conspicuity'. The first type refers to the possibility that an object will attract the attention of an observer who is not specifically looking for such an object. The second type, 'search conspicuity' is defined as the characteristics of an object that allow it to be easily and quickly localised if the observer is looking for it. According to Douglas & Booker (1977), this search factor can imply a large difference (factor 100 to 1000) with regard to, for example, the minimal luminous intensity required to 'find an object'.
Henderson et al. (1983) understand the conspicuity (of vehicles) to mean "not only that attribute of a vehicle that calls attention to itself as a stimulus, but also those attributes that contribute to the recognition of a stimulus as a vehicle and to the general understanding of what the vehicle is doing relative to the observer" (p. 145). In this definition therefore, both 'types' of conspicuity as described in the above seem to be represented.

Hughes & Cole (1984, 1986) summarise a number of factors that also determine whether an object will be conspicuous or not:
- physical properties of the object and its background;
- the information that is supplied, including information concerning the unusual or unexpected nature of the object;
- the observer's need for information (is the observer looking for a particular object? etc.);
- the perceptual strategy of the observer (road user), which is also determined by the information in his environment and his need for information.

## 2.3. Recognition, identification and the role of expectations

The most elementary form of perception is detecting whether 'something is there'. It becomes more complicated when someone must also indicate the category of object that 'something' belongs to: the recognition or identification of objects. The terms 'recognition' and 'identification' are often interchanged, and imply that an object is given the right label by an observer ("this is a car"). Some authors have noted that with recognition, one is only stating that the object concerned has been 'seen before', while identification implies more than that: the recognised object is identified as belonging to a particular category, e.g. a car (see, for example, Haber & Hershenson, 1980). With recognition and identification, factors such as experience and memory play a role. It is of course essential that road users 'see' relevant objects (in this case implying detection). But the detection of 'something' is generally insufficient to allow adequate decisions with regard to behaviour in traffic. This is why it is important that the correct interpretation is given to that which has been 'detected'; the correct meaning or identification must be associated with the visual impression, the image that falls on the retina.

An event or action can be generated by 'the surroundings', or by the observer who is actively looking for a particular part of the surroundings, or else by an interaction between these two processes. The distinction between the processing and perception of 'physical characteristics' and the observer's influence on this process of perception is also indicated by the terms for 'bottom-up' versus 'top-down' processes. Or as Anderson (1983) explains this distinction: "Bottom-up processing starts with the data and tries to work up to the high level. Top-down processing tries to fit high-level structures to the data. [..] Whether one studies tasks that are basically perceptual (that is, they start at the bottom of the cognitive system) or basically problem solving (that is, they start at the top of the system), one must address the issue of how top-down processing and bottom-up processing are mixed" (p. 127).

Various researchers (a.o. Hughes & Cole, 1984, 1990) have shown that the observer himself exerts significant influence on whether a particular object is noticed. An observer who <u>expects</u> to encounter objects with certain physical characteristics, will more readily 'see' them than when he does not expect them. LaBerge (1973) has shown in more fundamental research, for example, that test subjects will <u>more rapidly recognise</u> letters that they expect to see.

Finally, it can be noted that 'detection', 'conspicuity' and 'recognition' are all gradual matters and that 'visibility' (i.e. 'seeing' something) is in practice the outcome of all three factors. In practice, people are more or less satisfied with a degree of certainty; that they have seen something, that they know something is there or that they know what that 'something' actually is.

## 2.4. Applications in traffic

### 2.4.1. Detection

If it can be assumed that vehicles and their background represent uniform targets and drivers only needed to concentrate on detecting vehicles while always looking straight ahead, Blackwell's data could be put to use immediately to determine the conditions under which a 'standard' vehicle can be detected. However, vehicles are not uniform targets: they are made up of various types of paint, glass and chrome surfaces, etc. The road environment is not uniform either. In addition, it is not realistic to regard the driver as someone who is only concerned with the detection of vehicles. Therefore, it is not so easy to estimate how 'detectable' a vehicle is for a driver under all kinds of different (lighting) conditions.

The greater the contrast between the vehicle and its background, the greater the probability that it will be detected. For light coloured cars (paint), the contrast is generally greater than for dark coloured cars (e.g. see Allen & CLark, 1964; Dahlstedt & Rumar, 1976). But the contrast of a light coloured car against the background does not alter if the ambient illumination changes. Because the visual system's sensitivity to contrast diminishes with decreasing illuminances, the probability of detection will grow smaller as the ambient illumination drops.
Even on sunny days, the ambient illumination can vary considerably. The driver is not only confronted by a diversity of background luminances caused by the background itself, but also by more marked changes as the background alternates between shade and full sun. As a result, a vehicle that should be clearly visible in direct sunlight becomes relatively difficult to see in dark shade. The luminance of a light source, on the other hand, is constant - if the source is bright enough, its luminance will be greater than that of unlit objects in the surroundings. As the ambient

illumination decreases, the contrast between the light source and its background will actually increase. Therefore, if a vehicle cannot be properly detected for one reason or another, it is always 'advantageous' for that vehicle to use lighting. This is particularly true during twilight, poor weather conditions - e.g. during rain, mist and snow - and when the sun is very low on the horizon - e.g. sunrise and sunset. Even on very sunny days, a car without lighting can easily 'disappear' into the background, e.g. in the shade of buildings or trees. The use of lighting can ensure that - thanks to the heightened contrast - a vehicle can still be easily detected under such conditions.

### 2.4.2. Conspicuity and recognition

The incorrect selection of information from the surroundings (e.g at the wrong time, wrong information, etc.) can lead to accidents. The selection can occur both via 'top-down' or 'bottom-up' processes. Here we may use DRL to illustrate these processes. The lighting 'sec' could ensure that the observer will 'automatically' look in that direction (bottom-up; cf. 'attention conspicuity'), in fact without his being conscious of the fact; it is also possible that - as the observer knows that all cars will always use lighting - he will be actively looking for such 'cues' (top-down; cf. 'search conspicuity'). These processes can also be operating at the same time.

Hills (1980) emphasises the role of 'expectations' in traffic: "Another important factor affecting a driver's detection and perception of a potential hazard is his perceptual 'set' or his expectancies. These are formed both from long-term experience and by the short-term experience of the previous few minutes driving. These can profoundly affect the driver's interpretation of the various visual features and signals in a scene and also the various visual judgments he has to make" (Hills, 1980, pp. 190-193).

### 2.4.3. Illumination conditions and (voluntary) use of DRL

If the use of vehicle lighting is observed, it would seem that the ambient illumination is the best predictor. However, it is not the only one. For example, the weather plays an important role. In general, the use of lighting increases - at the same ambient illumination - as the weather becomes "wetter" (see e.g. Allen & Clark, 1964; Hisdal, 1973, quoted in Attwood, 1981; Williams, 1989).

In addition, recent observations made in the Netherlands (Lindeijer & Bijleveld, 1990) have shown that cars will switch on their lights at higher illumination levels during wet weather than during dry weather. At ambient illumination levels measuring 2000 lux, about 40% of motorists will use lights during dry weather, while during wet weather this ranges from less than 60% to over 90%, the average being 75% (see Figures 1 and 2).

### 2.4.4. Systematic coding

Therefore, there are other factors influencing the decision to use lighting, aside from the ambient illumination levels. Rabideau & Bhutta (1977, quoted in Attwood, 1981), offer the following factors in this regard: the type of weather as already mentioned, but also the season, type of vehicle and type of road. The ambient illumination proves to be the best predictor for the use of lighting. In all cases, there is also question of an enormous distribution in the use of lighting (see Figures 1 and 2). Not everyone will switch on their lights at the same time (with reference to illumination). This distribution means that even in situations where lighting is 'really essential', there will always be some vehicles that have not (yet) switched on their lights. The argument of 'homogeneity' has often been used with respect to road safety (e.g. see SWOV, 1969; Schreuder & Lindeijer, 1987). A disorganised multitude of (visual) elements in the field of vision can be dangerous, as it is then difficult to offer predictions about how the visual environment will look in the near future. The systematic coding of cars by means of lighting*, for example, can ensure that road users learn to expect that motor vehicles participating in traffic have their (head) lights switched on. In this way, they can be more immediately recognised as being relevant objects to take into

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* All cars painted in the same (light) colour would also offer an efficient coding system in this context, provided that the 'colour' coding does not indicate whether the car is actually participating in traffic: for example, a parked car will generally not use lighting and can therefore be recognised as 'not participating in traffic' at that moment; a 'red' or 'white' car will always be that colour, also when it is parked.

account, implying consequences for behaviour. Reversing this reasoning, this means that vehicles not using lights will no longer be 'expected', and therefore recognition will probably be delayed. The latter is only relevant with partial DRL use over a large percentage of users. Furthermore, homogeneity in the use of DRL - in any case under those circumstance where it is really necessary (i.e. during mist, heavy rain, twilight and the like) - means that everyone will at least be visible to the same extent.

# 3. GLARE

## 3.1. General

Until now, headlights were primarily used under conditions of darkness. In this context, designers of headlights have always had to face the dilemma of on the one hand, making lamps bright enough to allow the driver to see unlit objects far enough in advance to undertake action; on the other hand, to ensure that they are not so bright as to lead to unacceptable glare caused by oncoming traffic.

The effect of a 'glare source' can be described as a 'veiling luminance', i.e. an added background luminance, causing the contrast between the object and the 'original' background to become less and making the object less 'visible'. There has been a great deal of research conducted into the subject of glare and its negative influence on visual performance and subjective assessments. Obviously, glare is of particular relevance to night-time driving. Therefore, it is important that light beams are properly adjusted and oriented towards the right.
During the so-called recovery time associated with glare, part of the retina is 'out of action', so that other objects are also less visible, depending on the new direction of view. This recovery time for glare is brief and negligible at luminance levels of between approx. 100 and 3000 cd/m$^2$; however, at changes where the final intensity is less than several tens of cd/m2, the recovery time can assume considerable proportions (see for example Schreuder, 1987). So when there is (any) question of glare due to DRL, the eye will recover more quickly in this case than it would in the dark.

European low-beam headlights have a so-called "sharp cut-off", which minimises glare: a low luminous intensity just above the horizon, to prevent glare caused by oncoming traffic, and a higher luminous intensity just below the horizon so that the road etc. is well illuminated. In Europe, a glare intensity limit of 250 cd is set for low beam headlights (ECE, 1978); in the United States and Canada, the limit is set at 1000 cd. The glare intensity is the light of the low beam headlights that falls in the direction of the eyes of oncoming motorists. Alferdinck & Padmos (1988) found that in practice, however, a.o. due to dirt, age of the lamp, poor orientation etc., this glare intensity lies between 200 and 1000 cd in the Netherlands, with a median value of 500 cd. Special 'running lights' mounted on or beneath the front bumper are presently in use on 15% of Swedish cars. A Swedish standard was accepted in 1978 (SIS, 1978). Recently also ECE-regulations concerning daytime running lamps have been decided on that prescribe the surface area to be $\geq 40$ cm$^2$ and the luminous intensity 'straight ahead' between 400 and 800 cd (ECE, 1990). In the daytime, such values probably do not constitute a problem, but as twilight approaches, glare will become relatively more important. In a number of studies, the aspect of glare and DRL under various ambient illumination conditions has therefore been given special consideration.

The sensitivity of the visual system adapts to the luminance of the surroundings. In simple terms, this means that the eye becomes desensitised (to light) as the adaptation luminance increases. When objects appear in the field of view, their luminance differing greatly from one another, the eye must constantly adapt as it looks from one to the other. This is called 'transient adaptation' and temporarily reduces the ability to 'see', until the eye has again adapted to its 'new' luminance. Aside from transient adaptation, the literature also distinguishes between :

- '<u>discomfort glare</u>', also known in the Netherlands as 'psychological blinding' (German: 'psychologische Blendung'; Arendt & Fisher, 1956, quoted in De Boer, 1967);
- '<u>disability glare</u>', also known in the Netherlands as 'physiological blinding' (German: 'physiologische Blendung');
- <u>blinding glare'</u> , which can be regarded as 'absolute blinding'.

In general, glare may be understood to be caused by luminance in the visual field which is considerably greater than the luminance to which the eyes are adapted, and therefore results in discomfort, hinder, irritation or loss of visual performance and visibility.

"Discomfort glare" leads to 'feelings of irritation' or 'uncomfortable' perception, but does not necessarily interfere with visual performance or visibility*; "disability glare" leads to diminished visual performance and

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* Hereby it can be noted that the inability to measure 'diminished performance' does not necessarily mean that performance remains the same, as this is dependent on the sensitivity and validity of the 'performance measurements' used.

visibility and is often accompanied by 'feelings of irritation'; "blinding glare" finally is of such an intensity that for a considerable period of time, nothing can be seen, and people are literally blinded (see e.g. Kaufman & Christenson, 1972). 'Blinding glare' requires such high luminance levels, however, that this form of glare is hardly experienced in practice. In the following paragraphs, we will therefore restrict ourselves to 'discomfort glare' and 'disability glare'.

### 3.2. Discomfort glare ("psychological blinding")

Discomfort glare is the feeling of irritation or annoyance caused by high or irregular distributions of luminance in the field of view. The underlying processes causing discomfort glare are insufficiently documented. Much research has been conducted into the experiences of glare. As irritation or 'discomfort' is a subjective experience, it must be established by asking people to indicate the level of glare when exposed to a glare source (e.g. by giving it a particular 'score').

One of the measures used to indicate discomfort glare is called the BCD, the 'borderline between comfort and discomfort'. The BCD represents the luminance of a glare source assessed by an observer as being of such intensity that it just causes feeling of discomfort. The higher the BCD score, the less glare the light source, or the less sensitive the person is to the effect of that glare. The degree of discomfort glare is also related to the angle at which the glare source intersects the visual angle, the size of that source and the background luminance. Bennett (1977b; quoted in Sanders & McCormick, 1987) discovered a correlation of 0.26 of BCD with background luminance, a correlation of -0.41 with the size of the glare source and a correlation of 0.12 with the angle between source and direction of view.
Therefore, the greater the background luminance, the smaller the glare source and the greater the angle between glare source and direction of view, the less 'discomfort' will result. Bennett, however, noted that these three factors together only explain 28% of the variance in BCD assessments; individual differences between observers explained much more: 55% of the variance.
Various formulas have been devised that in some way relate aspects associated with 'light' to the subjective assessments of the amount of 'discomfort' experienced. Most follow roughly the following form:

$$\text{amount of glare experienced} = \frac{(\text{luminance of the light source})^{m} * (\text{size of the source})^{n}}{(\text{luminance of the background})^{x} * (\text{angle of source to direction of view})^{y}}$$

In general, the formula shows that as the luminance of the glare source increases, the size increases or the visual angle decreases, the degree of 'subjective glare' will increase; an increase in the luminance of the background will ensure a drop in the amount of glare experienced.

There are various ways to determine discomfort glare. The VCP method, for example (VCP = visual comfort probability) indicates the percentage of people that are still expected to find a particular degree of glare acceptable. The Glare Index system offers another method; it is an assessment scale along which people must indicate how glaring they find a source of light: varying from 'intolerable' to glare that is 'just inperceptible'. Other scales are also used - sometimes 6-point, sometimes 9-point - always following more or less the same principle (e.g. De Boer, 1967; Sivak & Olson, 1988).

All methods demonstrate a marked similarity, and the results obtained through the various methods therefore correlate quite well. However, it is still not known what exactly constitutes this 'discomfort glare' and what causes it. Markus (quoted in Boyce, 1981) even doubts whether 'glare' really means something to the majority of people. He feels it is an abstract term that does not agree clearly with the experiences people relate. When researchers ask people to indicate the degree of glare they experience, it is hardly surprising, believes Markus, that the results are so difficult to interpret: everyone has his own ideas of what constitutes glare. Markus also points out the significance of context; for example, people sit for hours in front of the television which, according to the formulas described in the above, produces 'intolerable glare'.

It can be concluded that little is in fact known about the psychological an physiological basis for the phenomenon of discomfort glare. At present, various methods are used to determine discomfort glare, of which the predicted measures of discomfort glare correlate quite well, the correlation between the predicted discomfort glare and the individual scores of observers is extremely low, however.

### 3.3. Disability glare ("physiological blinding")

Glare which interferes with visual performance and visibility is called 'disability glare'. Light entering the eye is scattered in the eyeball due to irregularities of the lens and the liquid in the eyeball. This scattered light creates a veiling luminance on the retina and reduces the contrast of the target viewed, making it less 'visible'. Each source of light in the visual field leads to a degree of veiling luminance on the retina. The effect this has on 'perception' is a function of the luminous intensity of the glare source and the angle at which it intersects the direction of view. The smaller the angle and the greater the luminous intensity, the greater its effect on 'perception'.
Even ordinary daylight can lead to disability glare. This is demonstrated when one wishes to watch television in the daytime while the set is positioned close to a window: sometimes it is impossible to see the picture at all*.

In the last decades, an enormous amount of research has been conducted into this type of glare. Formulas were designed which make use of veiling luminance, whereby the influence on perception is equivalent to the effects of glare. The general form of the formula is:

$L_{seq} = k\,(E / \Theta^{n})$

where $L_{seq}$ = the equivalent veiling luminance
$E$ = illuminance E (lux) on the eye
$k, n$ = constants
$\Theta$ = angle of glare source in relation to direction of view.

The values of the constants k and n vary, depending on age, angle of $\Theta$ and the like. Usually, a value of 10 is selected for k and a value of 2 or 3 for n (see also Stiles & Crawford, 1937; Vos 1983; and for overview also Schreuder & Lindeijer, 1987).
The national and international standards for lighting on motor vehicles take into account this disability glare. For example, the European stan-

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* (partially attributable to reflection)

dard states that the so-called glare intensity of low beam headlights in the direction of oncoming traffic must not exceed 250 cd. Discomfort glare is not referred to in any of the standards however; disability glare - which affects visual performance - is considered more important than discomfort glare. With the question of whether glare will result when using lighting during the daytime, the principal question in fact relates to whether - under particular conditions, e.g. twilight - discomfort glare would be an issue. In general, the luminance levels in the daytime will be so great - and, as a result, the difference in luminance between a headlight and the background will be so small - that there can be no question of disability glare. We will return to this question later on.

# 4. A QUALITATIVE MODEL

## 4.1. General

It is often stated that discomfort glare and disability glare represent two different types of glare. But when does each type occur? When can one 'observe well' without resulting in phenomena such as glare? These factors have been represented diagrammatically in Figure 3 (cf. also Hopkinson & Collins, 1970, p. 21). The horizontal axis shows the adaptation luminance in arbitrary log units, which is (a.o.) dependent on the ambient illumination level; the vertical axis shows the luminous intensity of the lamps, also in arbitrary log units. The area demarcated by curves in the above left and bottom right hand corner indicates the entire area within which perception (i.e. both detection, recognition etc.) is possible. Stimuli too dim to observe are situated in the area at bottom right; stimuli that are literally blinding, thus making perception impossible, are situated in the area above left. In the area where perception is possible, various subcategories can be distinguished. The lower area represents the threshold level for the detection of points of light, given certain adaptation luminances; above lies an area where discrimination is possible - allowing recognition and identification - without negative 'side effects' (the shaded area); above that is the area in which 'good' perception is still possible, but where a form of discomfort glare becomes apparent; the area above that indicates that disability glare will occur if lamps of this intensity enter the field of view of an observer*. Although detection is still quite possible, the 'details' are hard to observe due to disability glare.

The horizontal lines in Figure 3 indicate the luminous intensities of headlights. The graph illustrates that a headlight with luminous intensity A can be 'glaring' at very low levels of adaptation luminance, although within a large intermediate area of adaptation luminance, it falls into the 'well visible' area; this headlamp is never found in the 'too dim'

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* Disability glare relates to a glare source Y that makes the perception of an object X difficult or impossible; Figure 3 deals with the luminance of X.

detection area. A headlight with luminous intensity B is shown not to cause glare under any circumstances, but at relatively high adaptation luminances it falls into the 'too dim' category, so that it no longer contributes to visibility.

The preliminary lines in Figure 3 have been chosen so that their form and location roughly agree with existing knowledge or ideas in that regard. The lines showing the boundaries for disability glare and discomfort glare have been represented as a monotonically rising line, whereby the glare luminance increases disproportionately to the increasing adaptation luminances (e.g. De Boer, 1967). The detection curve is derived from research into threshold levels for the detection of point sources (see Douglas & Booker, 1977). The curve representing the boundary for 'absolute blinding' has been chosen on the basis that reports have indicated that both at very high and very low adaptation luminances, this form of blinding will sooner manifest itself than with the intermediate values (e.g. Vos, 1977). The dynamic range of the visual system, (within which 'good' perception is possible) is about 2 to 3 log units for every adaptation luminance (Pugh, 1988); such a range is also used in the model as depicted in Figure 3.

## 4.2. The model and DRL studies

### 4.2.1. Conceptual framework

To date, test results in the field of DRL and visual perception for various types of study (e.g. into detection, glare) have been conducted or reported more or less separately. Alternatively, such studies related to the question of when an 'improvement' (e.g. in terms of detection) would occur as a result of DRL, or when 'negative' side effects (e.g. glare) could be anticipated as a result of DRL. The model presented here represents an attempt to relate various types of study directly to each other, in order to obtain greater insight into the question of when positive or negative effects can be expected from DRL. In principle, the report is not intended to test model validity or indicate precisely the boundary lines as indicated in Figure 3. Its principal function is to offer a conceptual framework, within which various visual phenomena and studies can be summarised clearly.

If the model is able to achieve this aim, the next step would be to further quantify the model and assess its validity (range of application*)

Based on a number of studies, it will be attempted to quantify this conceptual impression somewhat further. The combination of luminous intensity of headlights used in DRL experiments will be repeatedly compared to the adaptation luminance. The luminous intensity will be expressed in cd, and the adaptation luminance in cd/m$^2$. As adaptation is dependent on the amount of light entering the eye, the luminance level is the most suitable variable in this case. Most studies do report the lighting conditions during the experiment in terms of illuminance (lux), but not in terms of luminance (cd/m$^2$).

According to the formula

$$\text{luminance} = \frac{\text{illumination x reflection factor}}{\pi}$$

illumination data can be converted to luminance values. If it may be assumed that the average reflection of the surface was 15% during the various studies (N.B. 10% reflection for asphalt road; 20% for grass), then the illumination data can be converted approximately to the adaptation luminance.

4.2.2. Threshold values

In Figure 4, the line indicating the threshold value is derived from data of Douglas & Booker (1977). Their graph shows the 98% detection boundary of a (point) light source as a function of the background luminance, expressed in foot Lamberts. This measure of luminance is easily converted to the more customary parameter cd/m$^2$ as follows: 1 fL = 3.426 cd/m$^2$. The

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* For example, the model does not take into account the visual angle. It is known that with peripheral vision, greater luminous intensities are generally required to cause 'glare' or 'improved detection' than with central vision. In addition, the size of the light source has not been taken into account; in principle, one size is assumed, i.e. that of an 'average headlight' (of some 100 cm$^2$). Further specification of the model will (also) take these factors into account.

threshold values indicated by Douglas and Booker are expressed in 'mile candles', a measure of illumination, and cannot be simply converted into candelas, the measure for luminous intensity. If it is assumed that the studies to be discussed in the following have an average observation distance of about 100 m, then (given the so-called square law of photometry):

$$1 \text{ cd} = \frac{1 \text{ mile candle}}{(1609)^2} * 100^2$$

The values thus obtained can be considered as extremely low values and are only valid if the observer knows exactly where to look for the source of light (Douglas & Booker, 1977, pp. 4-18). The authors note that even if the luminous intensity is doubled, the light source will be difficult to detect. The value must be increased by a factor of 5 to 10 for the source of light to be 'easily' detected (Tousey & Koomen, 1953). Douglas & Booker also note that these threshold values are only applicable if an observer is consciously looking for the light signal. A much stronger signal is required if it is intended to attract the attention of an observer who is not looking for the source; some feel factors in the region of 100 to 1000 are no exaggeration (see e.g. Kaufman & Christenson, 1972). Figure 4 shows the threshold value as given by Douglas and Booker, multiplied by a factor of 10 and converted to $cd/m^2$ and cd respectively; the line in this diagram primarily serves as a reference to offer an impression of the (enormous) area covered by 'perception'.

## 4.3. Detection experiments

### 4.3.1. Luminous intensity and detection distance

In this and subsequent paragraphs, studies are presented which relate to the question of when and how (visual) performance improves when vehicles use DRL, in comparison to the situation when they do not use their lights. It therefore concerns the definition of the 'intermediate area' (between detection and glare) in Figure 3, where the boundary which indicates where performance has not yet improved as a result of DRL is sought.

Hörberg & Rumar (1975; see also Hörberg & Rumar, 1979) conducted a number of experiments to examine the effect of luminous intensity, size and colour of headlights on the detection distance of approaching vehicles by an observer at various angles of view (30° and 60°). The experiment was conducted on the runway of a military air base. The ambient illumination varied from 3000 to 6000 lux. The researchers used lamps of 50 cd, 150 cd, 400 cd and 60,000 cd (high beam headlights) and compared the detection distance with that obtained when lighting was not used. The results showed that headlights must be brighter to detect vehicles at a visual angle of 60°, compared with detection at a 30° angle of view over the same distances. At 60° peripheral perception, a considerably greater luminous intensity (>400 cd) is necessary to improve the detection distance at ambient illuminations between 3000 and 6000 lux (early twilight). At a 30° visual angle, a luminous intensity of 400 cd causes the detection distance of a vehicle to almost double, when compared with the same vehicle without lighting (see Figure 5, from Rumar 1980). This is shown in Figure 4, where the point for the 400 cd lamp rises above the broken line.

Hörberg (1977; see also Hörberg & Rumar, 1979) used a similar experiment to study detection distances of vehicles at an angle of 20° for a number of different ambient illuminations, varying from 125 to 1750 lux. Lamps of 100, 200 and 300 cd were used. The results showed that the detection distance became greater as the luminous intensity of the lamps increased, up to a daylight illumination of about 1000 lux; the associated points are shown in Figure 4. At ambient illuminations measuring over 1000 lux, no improvement in detection distance was noted (none of the three light intensities).

Kirkpatrick et al. (1987) conducted a similar experiment. The detection distance of a vehicle that approached an observer at an angle of 15° was established under various daylight conditions. Lamps with a luminous intensity of 250, 500, 1000 and 2000 cd were used at ambient illuminations of 20,000 and 70,000 lux (bright daylight conditions). The results showed that the detection distance increased as the luminous intensity of the lamps increased. The average improvement in detection distance was about 24 m when the results for the 2000 cd lamp and the unlit conditions were compared. At an ambient illumination of 20,000 lux, an improvement in the detection distance was noted from light intensities of 1000 cd; at a greater ambient illumination of 70,000 lux, improvement was only noted after 2000 cd (see also Figure 4).

Attwood (1975; see also Attwood, 1981) performed a similar study, but at a much larger range of ambient illuminations. Figure 6 represents the result. Vehicles are detected sooner when the (low-beam) headlights were on than when they were off. It is assumed that the lamps have a luminous intensity of 600 cd (based on SAE standards). The detection distances were more or less constant over the entire range of ambient illumination when the vehicles used lighting. If they did not, the detection distance diminished as the ambient illumination decreased. At values of background luminance over about 100 cd/m$^2$, no further improvement was shown in detection distance if results were compared between the use (yes or no) of DRL; at lower values, the detection of a vehicle with lighting improved as the background luminance declined. A simulation of the experiment in the laboratory (Attwood & Angus, 1975) led to similar results. Figure 4 represents the results for a subset of four points; apparently, the distance to the broken line becomes increasingly smaller as the background luminance increases. In conflict with Attwood's study result, Figure 4 also suggests that at values measuring over 100 cd/m$^2$, improvement in detection is still noted.

### 4.3.2. Estimating distance and "gap acceptance"

Hörberg (1977) studied the effects of the luminous intensity of headlights on the estimation of distances. Test persons had to compare the distance to two parked cars standing on different carriageways at a distance of between 250 and 550 m from the observer. One of the cars did not have its lights on, the other did (luminous intensity of 300 or 900 cd). The distance between the vehicles was 0, 15, 30 or 60 m and the test subject had to decide within several seconds which of the two cars was closest. The ambient illumination was 4000-5000 lux. Apparently, as the luminous intensity of the headlights increased, the estimated distance to that vehicle became smaller. In other words: If both vehicles were at the same distance from the observer, the vehicle with lights on was estimated to be closer than the unlit vehicle. It can be assumed that estimating a vehicle to be closer is 'safer', as a driver will respond more rapidly. The associated points in Figure 4 are both found above the broken line, therefore indicating a 'better performance' than would be the case without lighting.

Attwood (1976; see also Attwood, 1981) studied whether lighting on vehicles at various background luminances exerted an influence on 'gap acceptance'. Test subjects had to decide in a simulated overtaking task when they could just overtake with safety, while a car (with or without lights) was approaching. The minimal accepted 'gaps' varied, both depending on the intensity of the headlamp and the background luminance. Attwood does not refer to the luminous intensities of the headlamps used, although he does report that a 'low-beam' and a 'reduced low-beam' lamp were used. The estimated luminous intensity of the 'low-beam lamp' is 600 cd (based on the SAE standard), that of the 'reduced low-beam lamp' is estimated at 200 cd. At a background luminance of 343 cd/m$^2$, the 'low-beam lamp' resulted in a considerably larger 'gap' (70 m) acceptance when compared with the situation without light, or with the 'reduced low-beam lamp' (20-25 m). At a very low background luminance (4.6 cd/m$^2$) the 'gaps' had to be far greater before they were accepted as 'just safe', both with the 'low-beam' and with the 'reduced low-beam lamp' (120 to 50 m respectively). The acceptance of a larger gap can be interpreted as a 'safer' performance with respect to the situation without lighting. Therefore, Figure 4 shows the 343 cd/m$^2$ situation to be above the broken line for the 600 cd point, but not for the 200 cd point (the accepted 'gap' in this case was no greater when compared with the situation without lighting). For the 4.6 cd/m$^2$, both points are situated above the broken line. The figure also suggests that the low-beam headlight will just avoid discomfort glare at low luminances (almost dark).

### 4.4. Subjective assessments of visibility and glare

Figure 7 shows the experiments related to glare and other subjective assessments. The top broken line indicates the boundary above which 'discomfort glare' will occur; the lower line shows - as in Figure 4 - the boundary level above which an 'improvement with respect to the situation without lighting' is observed.

#### 4.4.1. Assessments of visibility

Hörberg & Rumar (1975; see also Hörberg & Rumar, 1979) assessed the relative visibility of vehicles by means of 'paired comparisons'; test subjects had to indicate which of two vehicles was 'more visible'. One of the cars always used lighting (50, 150 or 400 cd), while the other did not. The ambient illumination was about 2500 - 5000 lux. The results showed that the test subjects even thought that a car fitted with a 50 cd lamp was more visible than a car without lights; better visibility however only became clearly apparent at 400 cd. Figure 7 shows that the 400 point is clearly over the line, representing an 'improvement with respect to the situation without lighting', while the other two points are not over this line.

Allen & Clark (1964) established 'visibility' with the aid of a 'visibility meter'. They noted that a lamp of 21 cd mounted to the front of a car at an illumination of 2000 ft cd ( = 21.529 lux) was just as 'visible' as a black car. At 750 ft cd ( = 8.074 lux), the 21 cd lamp was just as 'visible' as a white car; at 250 ft cd ( = 2.691 lux), the 21 cd lamp was better visible than cars without light. The article by Allen and Clark does not clarify exactly how this 'visibility meter' worked. If the points are entered into Figure 7, the results of the experiment do not agree with the interpretation that is given in accordance with the figure: in all three cases, the points are well below the broken line.

### 4.4.2. Recognition

The previously described detection experiments generally required the test subjects to detect one vehicle in an otherwise empty traffic area. In addition, the test subjects always knew what they were supposed to see: a car. The experiments described in the above are in fact only applicable to road users who are alert, look in the right place at the right time and know which (type of) object they can expect.

In reality, all types of lit and unlit vehicles and road users (and other objects, lit or otherwise) will be found on the road; whether the results of detection experiments are relevant to these situations is not certain. It is therefore recommended that an experiment be conducted in which test subjects should not only detect road users - not necessarily cars alone - but should also identify or recognise them as pedestrians, cars, cycles etc. The 'correct recognition' can then be demonstrated by the correct naming of the object, or from the 'correct' (traffic) manoeuvre the test subjects are expected to carry out. Such an experiment could assess whether cars with DRL are also better recognised as such; the lighting can then be regarded as extra coding, and foster a certain expectation of a vehicle 'participating in traffic', in contrast to a parked car, for example without lighting). As to date, little attention has been paid to such cognitive processes in studies on perception in the field of road (safety) research, it is recommended that a study be carried out to examine to what extent 'top-down' influences could play a role with measures such as DRL, for example.

The schematic model (Figure 3) assumes that recognition and identification performance also improves as the luminous intensity of lamps increases. Whether this is indeed the case will have to be established on the basis of studies. One indication that the identification performance does indeed increase as luminance levels rise can be deduced from a laboratory study conducted by Hagenzieker et al. (1990). Test subjects had to name letters which either had a 'high' (10 $cd/m^2$) or a 'low' (0.2 $cd/m^2$) luminance. The results showed that the identification performance improved under high luminance conditions. Strikingly enough, the localisation performance was not affected when the high and low luminance conditions were compared to each other. Apparently, two more or less independent components or processes are involved in 'recognition': localisation and identification. It must be noted that this laboratory task is still far removed from 'reality', and generalisation on the results is a risky business; it serves to illustrate that "recognition" and "identification" may be important dependent variables which demand further study, also in relation to DRL.

### 4.4.3. Assessments of (discomfort) glare

In terms of the model of Figure 3, studies relevant to assessments of glare are particularly concerned with finding a boundary between 'good' perception (without annoying side effects) and the occurrence of glare. Kirkpatrick & Marshall (1989) studied the extent to which headlights (at various light intensities) caused discomfort glare at an average ambient illumination of about 1900 lux, when observers see the lights of an approaching car in their rear-view mirror. Light intensities of 500, 1000, 2000, 4000 and 7000 cd were used.

The subject had to indicate on a 9-point scale (De Boer scale) how annoying they felt this glare to be. The results showed that the 2000 cd lamp was considered by 80% of test subjects to be 'just admissible', while lamps of over 2000 cd were regarded as unacceptable or disturbing; the 1000 lamp was considered 'satisfactory'. In a previous experiment, Kirkpatrick et al. (1987) studied discomfort glare via rear view mirrors as well; in this case, the average ambient illumination was about 700 lux. Lamps of 500, 1000 and 2000 cd were used, and test persons considered the 1000 lamp to be just admissible. It has been established earlier that the discomfort glare luminance does not decrease in direct proportion to increasing adaptation luminance (De Boer, 1967); the results of Kirkpatrick et al. therefore agree with the finding. The points for both experiments are shown in Figure 7; both ambient illuminations indicate that lamps from 2000 cd upwards would lead to discomfort, according to the figure. However, Kirkpatrick & Marshall deduced from their results that the difference in the average ambient illumination cannot be the cause for the varying assessments in both experiments (as the figure would suggest). They concluded that when the different ambient illuminations are taken into account, the 1989 experiment still judges the 2000 cd lamp as being 'just admissible'. Kirkpatrick & Marshall suggest that the difference in the findings can probably be attributed to the so-called range effect; in the second experiment, the light intensities of the lamps varied from 500 to 7000 cd, while in the previous experiment, they ranged from 500 to 2000 cd. Test subjects could therefore base their assessment on the relative discomfort they encountered, taking into account the range of light intensities to which they were subjected.

Sivak et al. (1989a) also pointed out that previous exposure or 'experience' (albeit of an entirely different order of magnitude) also plays a role in the discomfort glare experienced. In one experiment, Americans and a group of Germans who had just arrived in the United States were asked to assess headlights on the degree of discomfort glare. The luminous intensity of European low-beam headlights is less than that of the American lights. The results showed that the Germans experienced significantly more discomfort from the (American) headlights than did the American test subjects; assessment of glare therefore seems to be associated with previous experience.

Not only experience, but age also seems to have a bearing on the assessment of discomfort glare, where older persons suffer from the effect before young persons do (see Kirkpatrick et al., 1987; Olson & Sivak, 1984; Pulling et al., 1980). Age differences are not always found however, as the previously cited study by Kirkpatrick & Marshall (1989) was unable to demonstrate any age effect with the assessment of discomfort glare. This is not that strange, as there are no physiological reasons why discomfort glare should increase with age, although the latter cannot be said for disability glare with age. These two types of glare can occur at the same time, also in the course of experiments.

Sivak et al. (1989b) discovered a relationship between discomfort glare experienced and task difficulty. Apparently, the more difficult the task required of the test subject, the greater the discomfort glare experienced. In addition, test subjects that did not perform the task well experienced greater discomfort from the glare stimuli than did test subjects that performed the task successfully.

During a DRL test in Florida (SAE 2987), observers assessed whether DRL of various light intensities under various ambient illuminations and various visual angles "could be seen", and to what degree. The following scale was used: 0 - DRL not noticeable; 1 DRl; slightly noticeable; 2 - DRL noticeable; 3 - DRL very noticeable; 4 - DRL too bright. When assessments of observers fell into the 0 or 4 category, these were regarded as unacceptable. The general conclusions of the test were that at small observation angles, assessors noticed the lamps more rapidly than at more peripheral angles of view; they noted the lamps more readily at short, rather than long distances, while lamps with a luminous intensity of 5000 cd were considered by many observers to be 'too bright' under all test conditions. Figure 7 depicts several points associated with this test. At an ambient illumination of 90,000 lux, the lamps with a luminous intensity of 600 cd (angle of view 8°; distance 152 m) were hardly noticed; therefore, this point is shown below the broke line in the figure. The 1500 cd lamp was more noticeable and that of 5000 cd even more so, although not yet considered 'too bright' by most observers (although the figure would suggest this). At a much lower level of ambient illumination (approx. 8000 lux), the 600 cd lamp was also clearly distinguished, and is therefore shown above the broken line in Figure 7.

In a similar test (SAE, 1989) conducted in Washington, D.C., observers assessed whether lamps measuring respectively 200, 400, 500, 1000, 2000, 2400 and 7000 cd were considered to be 'lighted' (yes or no) and whether they were regarded as glaring (yes or no) at two levels of ambient illumination: approx. 40,000 lux and 800 lux. The results showed that all lamps, both during daylight and twilight conditions, were regarded by over 80% of test subjects as being 'lighted'. With the daylight test (40,000 lux), it was also shown that from about 2400 cd, lamps were considered to be glaring by over 20% of assessors; during twilight conditions, this percentage was already seen with lamps from approx. 1000 cd (see also Figure 7).

In past years, the SAE has conducted a broad series of DRL tests, comparable with the tests described in the above (see CIE, 1990; SAE, 1990). A summary of these tests and their results can be found in Appendix 2.

### 4.5. Summary of the results

When we summarise Figures 4 and 7 and condense them into one, Figure 8 is the result. This new figure in fact quantifies the previously presented model as shown in Figure 3. If we then assume that the broken lines - which respectively show the boundaries above which some form of improvement in visual performance or assessment occurs when compared with the situation without lighting, and the boundary above which discomfort glare occurs - are correct, then the area between the broken lines offers a indication of the desirable luminous intensity of vehicle lighting.

At background luminances of roughly 1 cd/m$^2$ and below, we can speak of 'darkness'; background luminances between 1 and about 100-200 cd/m$^2$ are found during twilight; above this value one can speak of 'daylight'. See Figure 9 for some examples of luminance values for common situations.

Figure 8 shows that the higher the adaptation luminance, the greater the luminous intensity must be to still effect an 'improvement' with respect to a situation without lighting, and the greater the luminous intensity can be before any form of glare becomes apparent. It therefore follows that whatever the luminous intensity eventually chosen, it will always be difficult to strike a balance between 'desirable improvement' and 'undesirable glare'. Under 'daylight conditions' (> 100 - 200 cd/m$^2$) at a luminous intensity of 1000 cd, there will virtually never be any form of glare, while an improvement of visual performance or assessment can be anticipated. However, during the twilight period, glare can be experienced, even at a luminous intensity of 1000 cd. If, for this reason, a lower luminous intensity is selected, for example 400 cd, this will not offer any 'improvement' with respect to the situation without lighting under very bright daylight conditions, e.g. at 1000 cd/m$^2$ or greater.

Padmos (1988) also points out this trade-off between the required luminous intensity on the one hand and the current illumination level on the other. He associates the luminous intensity of the headlights with the percentage of daytime (average per year, at average latitudes, e.g. as found in the Netherlands) when the lamp still contributes to the conspicuity - in terms of detection distances - of a car. He concludes that, if from the point of view of limiting glare it is desirable to restrict the luminous intensity to 250, 1000 or 2000 cd, the percentage of daytime in which DRL light will enhance conspicuity will be 8%, 46% or 76%, respectively. The ambient illumination in the daytime (horizontal) on which Padmos (1988) bases his calculations is measured in the "open field", i.e. without 'obstacles' or other surrounding background objects being present. For this reason, the percentages quoted at 8%, 46% and 76% respectively will be on the low, cautious side; a road user generally will not be travelling through the open field, but through cities, forests etc., and experience constantly varying luminances (generally lower than those measured in the open field).

## 5. OTHER STUDIES

This chapter finally will summarise several studies where the results could not be fitted into the previous diagram. This relates to studies where the effect of vehicles using light is studied with regard to the detection of vehicles not using lights. Some studies have also looked into the possible masking effect DRL would have on brake lights and indicators. Attwood (1977, 1979) examined the extent to which vehicle lighting affects the detection of an unlit vehicle. The results showed that if an unlit car must be detected between two cars with low-beam headlights, it would be more difficult to detect than if all cars used the same lighting (or were all unlit). This effect increased as the ambient illumination decreased or the luminous intensity of the lamps increased; the effect was therefore greatest during the period of (low) twilight.

An associated question is whether the introduction of DRL will make slow traffic - such as pedestrians and cyclists - relatively less visible or conspicuous. Riemersma et al. (1987) studied changes in the conspicuity of cyclists (without lights) in the vicinity of a car using lights. The conspicuity was measured with a special 'conspicuity meter' (see Wertheim, 1986; Wertheim & Tenkink, 1987), whereby the conspicuity was determined by establishing to what extent contrast could be reduced, until the object to be measured fell just below the borderline of visibility. In addition, eye movements were recorded, and test subjects underwent a naming experiment in which they had to relate what they saw at various scenes. With each of these three experiments, results showed that the lighting increased the conspicuity of the vehicle, without adversely affecting the conspicuity of the cyclist.

Whether lit vehicles can actually cause unlit road users (other cars or slow traffic) to be less easy to detect or less conspicuous is therefore impossible to measure on the basis of these two studies, as superficially at least, the results seem to be in conflict with each other.

Kirkpatrick et al. (1987) report a study in which the masking effects of DRL were assessed in relation to indicators. They found that at a luminous intensity of 250 cd for the indicator and a range of 500 to 2000 cd for DRL, the viewing distance affected the masking effect as did the lamp surface, although no major effect of DRL luminous intensity was found. If special 'running lights' are not present, the back lights also switch on when lighting is used in the daytime. Various authors have pointed out that the rear lights are not bright enough to mask the brake lights (Rumar, 1981; Attwood, 1981). Based on the available studies, it would be fair to conclude that DRL will not cause the masking of brake lights or indicators.

Helmers (1988) suggests that negative side effects of DRL, such as the masking effect described in the above, do not weigh up against the positive effects of this measure; therefore, one can speak of a positive net result. Future studies, both accident studies and studies relevant to perception and behaviour, must demonstrate whether this Swedish claim is justified.

## 6. CONCLUSIONS AND RECOMMENDATIONS

1. The results of extremely diverse types of studies - relevant to detection, gap acceptance and subjective assessments of visibility and glare - can be incorporated into one schematic model.
The purpose of the model presented in this report (see also Figures 3 and 8) was not to assess or define precisely the limits as indicated. In principle, it was used to relate the many different types of study to each other within one conceptual framework. Now that this has been shown to be feasible and the results combined to form a comprehensible whole, the next step will have to be to study the validity of the model (its applications) and to further specify the boundaries assumed to date.

2.a) Detection distances are greater for vehicles with lighting when compared to unlit vehicles.

b) When using DRL, the minimal gap acceptance is greater than when lighting is not used.

c) Subjective assessments have shown that vehicles with DRL are more visible that vehicles without DRL.

d) According to the model as presented in this report (see Figure 8), these improvements in performance and visibility should already occur with lamps from 100 cd at low adaptation luminances up to about 50 cd/m$^2$ (twilight); for higher adaptation luminances, higher luminous intensities are required, e.g. lamps of at least 300 - 400 cd at 1000 cd/m$^2$ and at least 2000 cd at adaptation luminances of about 5000 - 6000 cd/m$^2$.

3. There is a grey area between the wish to avoid signs of glare on the one hand and the wish to improve visual performance on the other. For example, according to the model, a lamp of 1000 cd could result in symptoms of (discomfort) glare at an adaptation luminance below about 50 - 100 cd/m$^2$ (similar to twilight conditions). If there is question of glare due to DRL, this will be of particular relevance during twilight hours (also depending on the luminous intensity selected, of course).
This applies especially when special DRL-lamps (i.e. no low-beam headlights) are used; when low-beam headlights are used as DRL the glare problem during twilight conditions is irrelevant in the way that such glare is not a specific "DRL-problem" then.

4. In consideration of the paradox referred to in the above, it is important to study precisely what the possible 'ideal' luminous intensity range should be for DRL lamps; in this regard, the need to avoid glare and the wish to improve visual performance must always be weighed up against one another.

5. One disadvantage of the studies on which the results discussed in this report are based is that test subjects always knew exactly what to expect; this is not very realistic, and it would therefore be advisable to conduct similar research in future under conditions more relevant to the true traffic situation.

6. The effect of DRL on recognition or identification has not yet been studied; remarkably little is known about its effect on (other) cognitive processes, decision-making and (traffic) behaviour under dynamic conditions. It is recommended that these aspects be the subject of future study.

7. The study results available with regard to the question of whether lighted vehicles hamper perception of unlit road users have led to conflicting findings for different vehicle/road user-types. Further study is required.

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<u>FIGURES 1 TO 8</u>

Figure 1. Percentage of cars using DRL during wet weather and/or wet road conditions (Source: Lindeijer & Bijleveld, 1990).

Figure 2. Percentage of cars using DRL during dry weather and dry road conditions (Source: Lindeijer & Bijleveld, 1990).

Figure 3. Schematic representation of the qualitative model.

Figure 4. Detection and gap acceptance experiments. The horizontal axis shows the adaptation luminance (of the background); the vertical axis shows the luminous intensity (of one (head)lamp with a surface area of appr. 100 $cm^2$). The points over the broke line indicate that 'performance' (detection; gap acceptance; distance estimation) is 'better' as compared to the situation without DRL.

Figure 5. Detection distance during daylight at two angles of view in relation to light intensity and size of headlights (Source: Rumar; 1980).

Figure 6. Detection distance versus background lumination with and without DRL (Source: Attwood, 1981).

Figure 7. Glare and subjective assessment experiments. The points over the broke line indicate that 'performance' (subjective improvement/ assessment) is better as compared to the situation without DRL. The points situated over the dotted line indicate the occurrence of (discomfort) glare.

Figure 8. Summary of DRL experiments.

Figure 9. Some examples of (approximate) luminance values for common situations (see also Appendix 1).

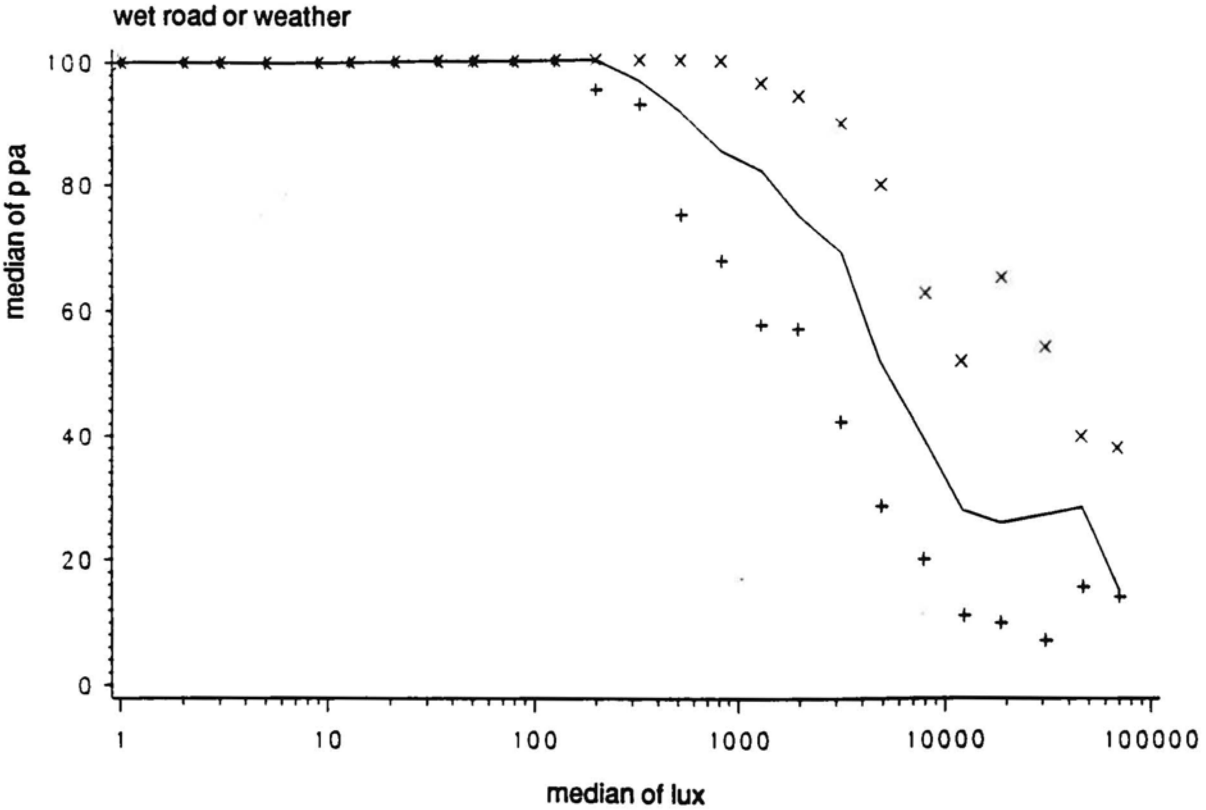

Figure 1. Percentage of cars using DRL during wet weather and/or wet road conditions (Source: Lindeijer & Bijleveld, 1990).

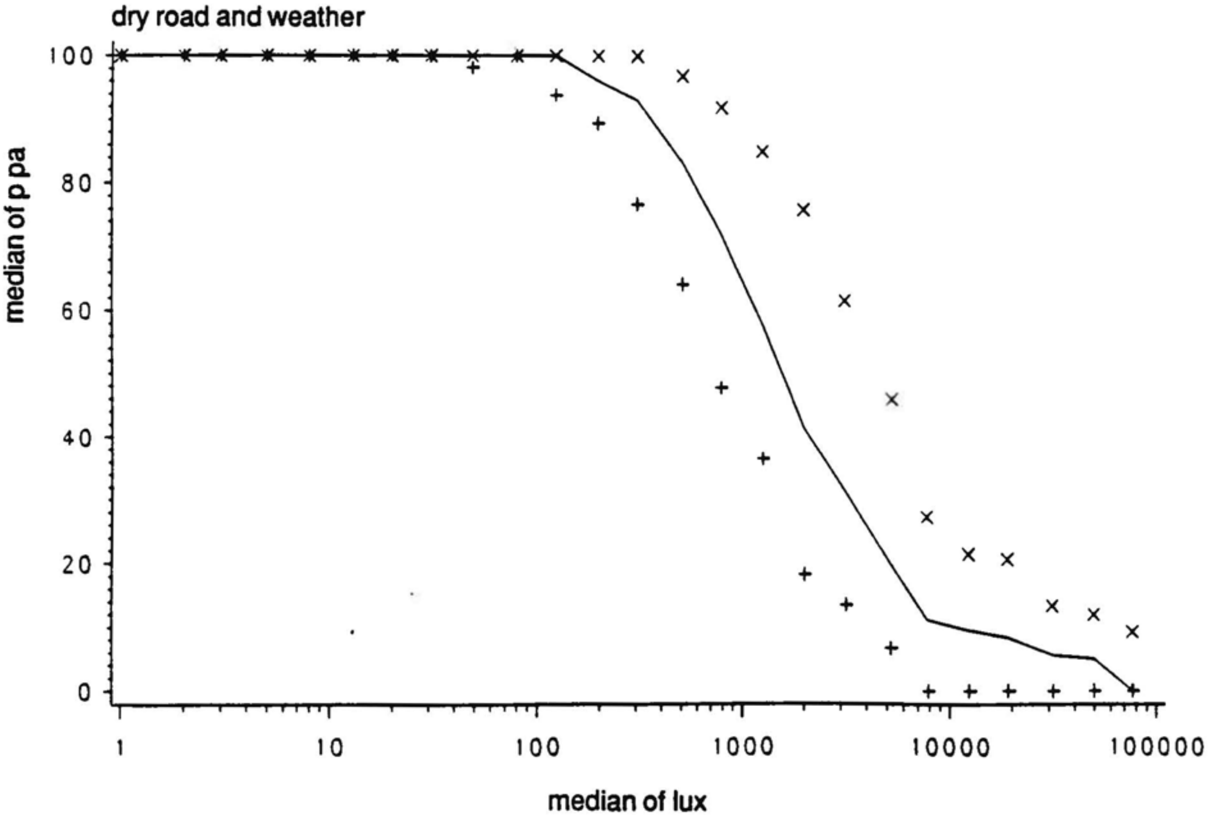

Figure 2. Percentage of cars using DRL during dry weather and dry road conditions (Source: Lindeijer & Bijleveld, 1990).

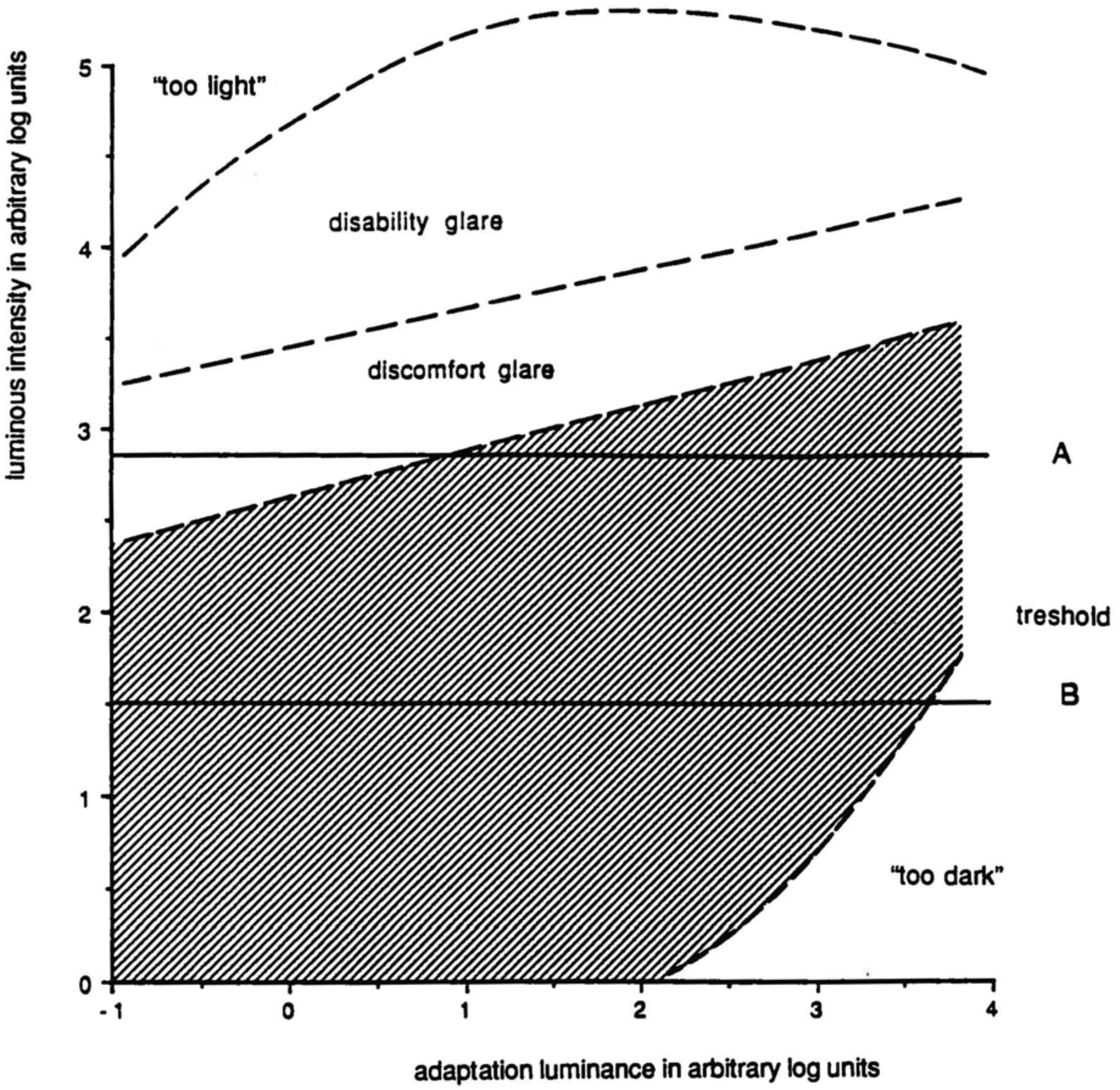

Figure 3. Schematic representation of the qualitative model.

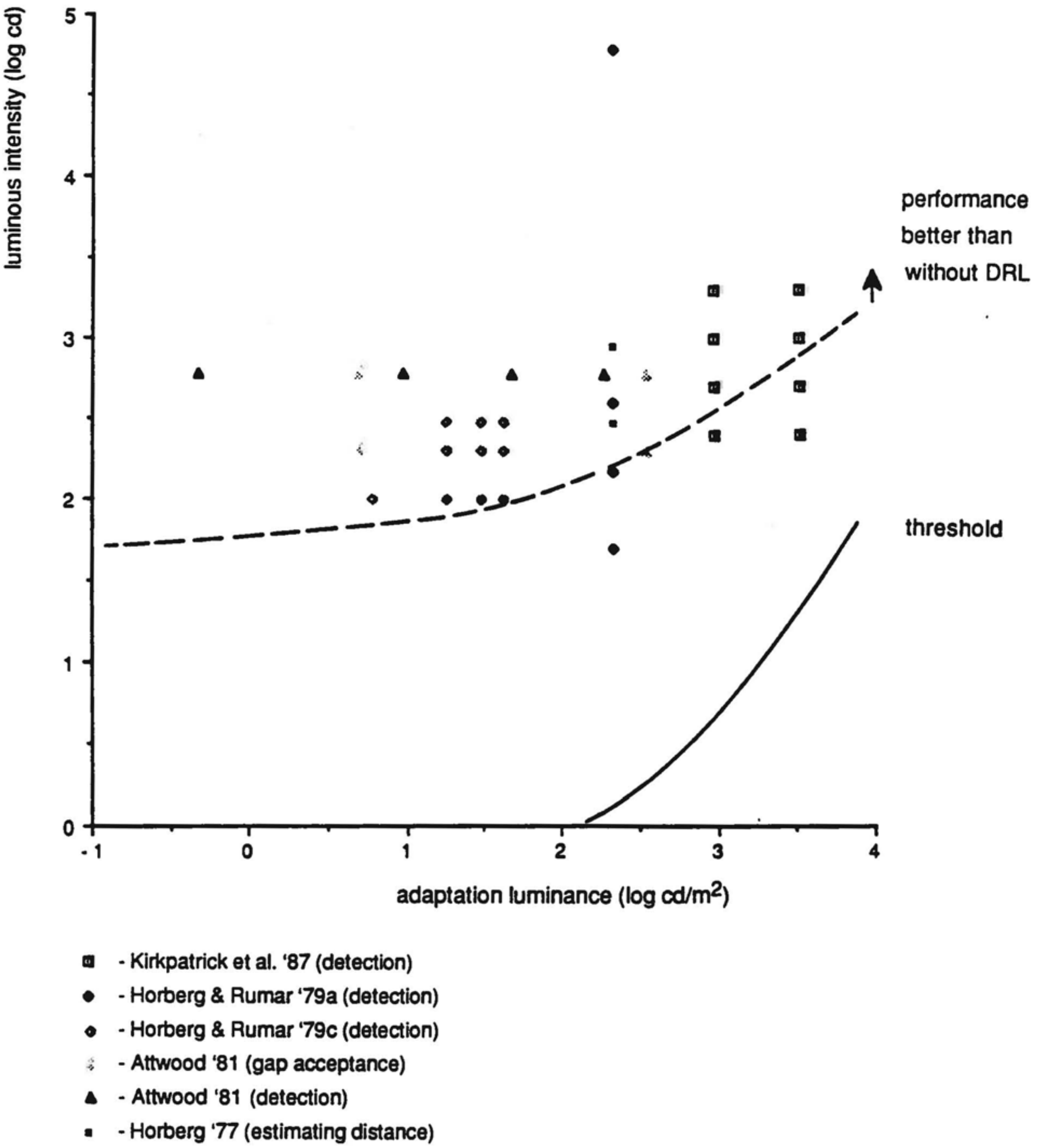

Figure 4. Detection and gap acceptance experiments. The horizontal axis shows the adaptation luminance (of the background); the vertical axis shows the luminous intensity (of one (head)lamp with a surface area of appr. 100 cm$^2$). The points over the broke line indicate that 'performance' (detection; gap acceptance; distance estimation) is 'better' as compared to the situation without DRL.

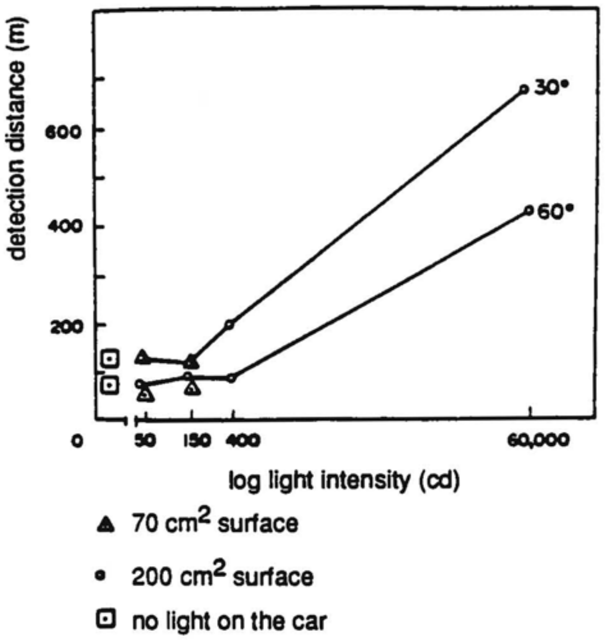

Figure 5. Detection distance during daylight at two angles of view in relation to light intensity and size of headlights (Source: Rumar; 1980).

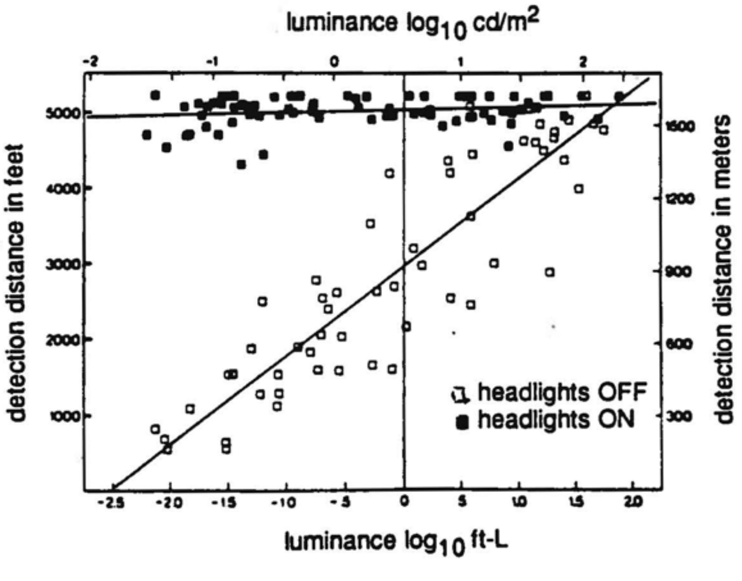

Figure 6. Detection distance versus background lumination with and without DRL (Source: Attwood, 1981).

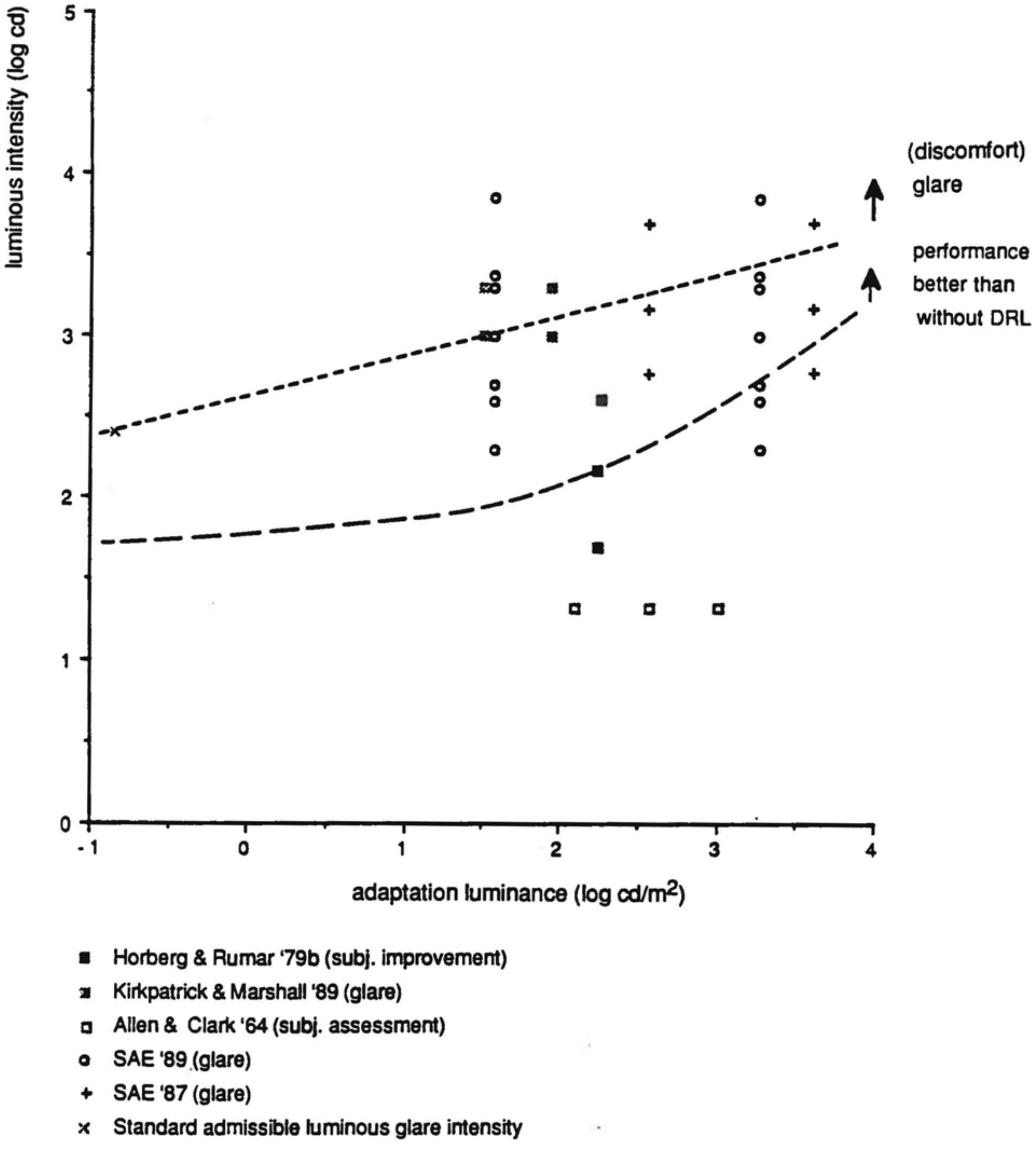

Figure 7. Glare and subjective assessment experiments. The points over the broke line indicate that 'performance' (subjective improvement/ assessment) is better as compared to the situation without DRL. The points situated over the dotted line indicate the occurrence of (discomfort) glare.

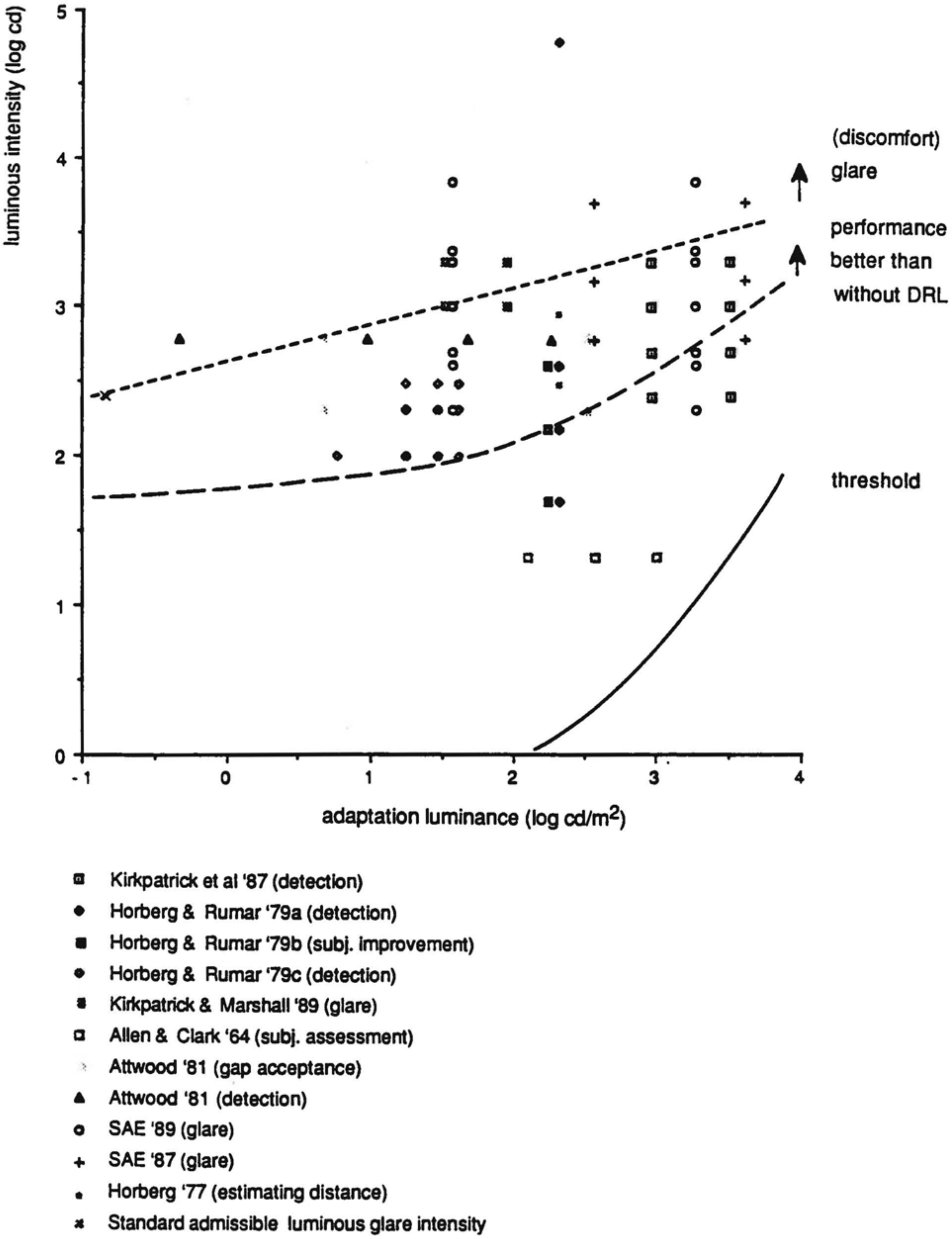

Figure 8. Summary of DRL experiments.

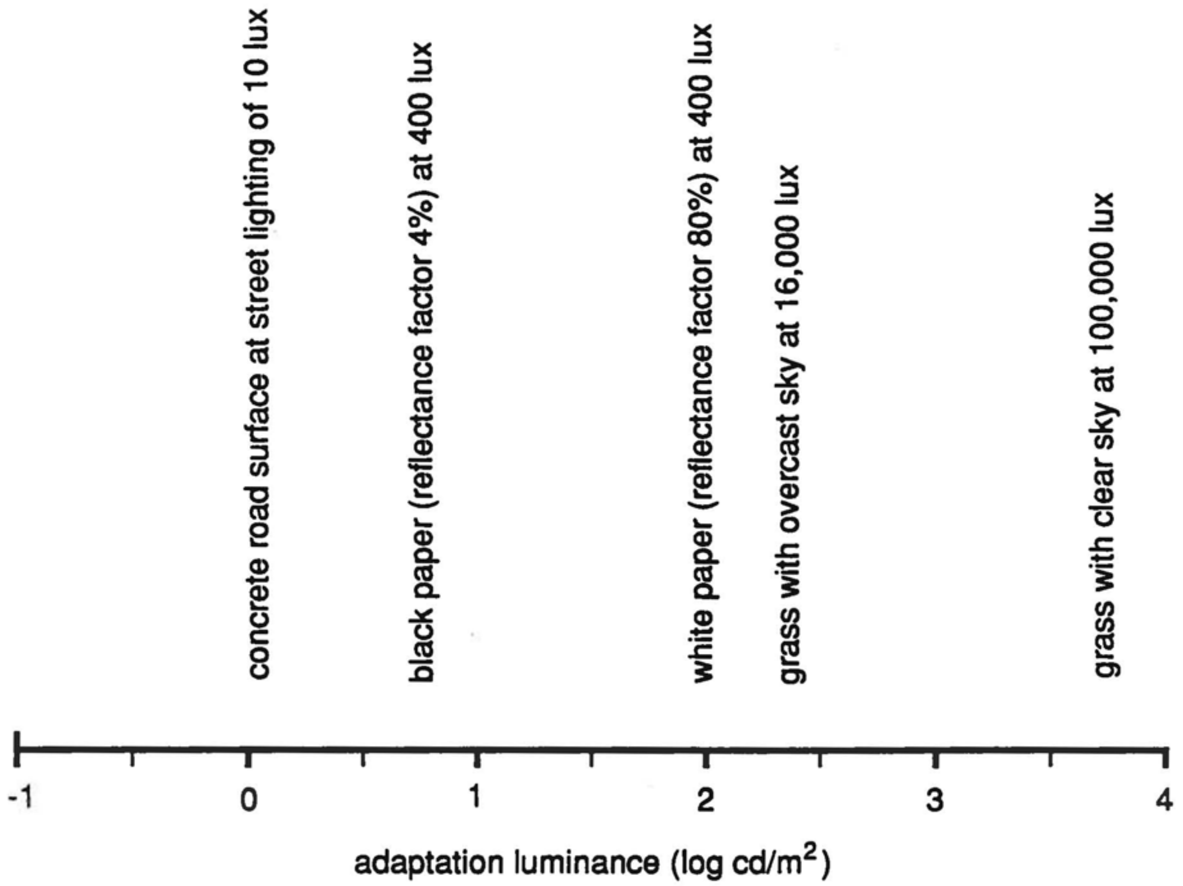

Figure 9. Some examples of (approximate) luminance values for common situations (see also Appendix 1).

## APPENDICES 1 AND 2

Appendix 1. "Light"

Appendix 2. "Summary SAE DRL-tests" (1990)

## APPENDIX 1

## "LIGHT"

Some concepts with regard to "light" and its measurement are explained in brief.

The concepts of "light" and "seeing" are inextricably linked: electromagnetic radiation that can be "seen" is known as "light". The electromagnetic spectrum has a large number of different types of radiation, i.e. forms of vibration that all have the same speed but differ from each other in frequency and wavelength.

Very short wavelengths are invisible, as are very long ones. The wavelength of radio waves can extend from several metres to a number of kilometres, the wavelength of infrared radiation is expressed in microns, while the wavelength of visible radiation and ultraviolet radiation is expressed in nanometres (also known as: millimicrons, i.e. $10^{-9}$ metres). The area of "visible radiation" lies within the narrow wavelength field of about 380 - 760 nanometres (nm); on one side it is bounded by ultraviolet radiation (with a shorter wavelength), while on the other it is bounded by infrared radiation (with a longer wavelength). These two forms of radiation are therefore "invisible".

Often, colours are associated with the various wavelengths in the visible spectrum. Wavelengths of about 400 nm are seen as violet, those measuring 500 nm as blue-green, those of 600 nm as yellow-orange and those of 700 nm as red. However, colour is not so much a property of light as of the visual system: the perception of colours is dependent on much more than wavelength alone.

The visual system is not equally sensitive to light at various wavelengths. For light at different wavelengths, the same number of quanta (light particles) do not give the same impression of brightness or allow detection to the same degree. Neither is it true that these differences are constant under various light conditions to which the eye has adapted. Specifying the amount of radiomagnetic energy in a particular stimulus in fact offers no information about the visual response that such a stimulus might or might not arouse. Therefore, a measurement system was developed to express electromagnetic energy in terms relevant to "seeing". This system is known as photometry. The so-called spectral sensitivity curves as used by the CIE (Commission Internationale de l'Eclairage) specify the relative sensitivity of 'the eye' to various wavelengths and under various light conditions. There is no spectral sensitivity curve for the visual system which is equally applicable to all people under all circumstances. For example, under relatively "light" conditions, where the cone system is active ("photopic seeing"), the eye is most sensitive to wavelengths of about 555nm; under relatively "dark" conditions, where only the rod system is active ("scotopic seeing"), the eye is most sensitive to wave-lengths of about 505 nm.

The measurement of light is therefore based on the visual effects caused by visible radiation. Photometric units are used to describe the stimulus. Every aspect of light is measured separately and expressed as a particular unit. Through the years, a jungle of photometric units has been created, as every scientific or technical discipline developed its own units. It is impossible to deal with all of these units here. In brief, several light measures will be described, specifically those agreed to in an international context: those based on the Système International d'Unités (the SI-system).

The total amount of light radiated by a light source per second is called the luminous flux, and is expressed in lumen (lm).
The luminous intensity is the luminous flux radiated in a particular direction, and is expressed in candela (cd).
The illuminance or illumination is the amount of light that falls onto a surface, and is expressed in lux (= 1 lumen/$m^2$).

A surface that radiates light can be a light source (a lamp, "primary light source"), or a source that reflects an incident light ("secondary light source"). In both cases, the light source leaves an impression of brightness. The photometric measure for this is the luminance (expressed in cd/$m^2$). Formerly, luminance was also referred to as photometric brightness. The percentage of light reflected off a lit surface is called the reflectance, and is expressed by the reflectance factor (in percentages). When a surface is very smooth, the photons (light particles) are not scattered in all directions but reflect in a concentrated beam. In the most extreme case of a perfectly reflecting surface, photons are only reflected in one direction: namely directly opposite to the angle at which they hit the surface. Objects with high reflection values seem very bright, as virtually all light that falls on the object is reflected back to the eye. That is why a black surface always look dark, regardless of the amount of light falling on it, as virtually all light is absorbed. Brightness is therefore an impression observers receive from a particular light stimulus.

For example, imagine a car headlight lighting up a traffic sign; the amount of luminous energy leaving the lamp determines the luminous flux; the amount of light incident on the sign is the illumination; the amount of light reflected from the sign is the luminance and what the observer 'experiences' when he looks at the sign is the brightness.

Brightness is not only dependent on the amount of light that falls on the eye. When brightness is compared to the (photometric) luminance, a non-linear relationship is seen. Brightness is related to many different factors: for example, the wavelength of the light, the adaptation condition of the observer, the size of the object, its contrast with the background, the length of exposure, the shape, whether the object is observed centrally or peripherally, etc. Without entering into further detail, it will now be apparent that "seeing" is impossible without "light", but that "light" is not the only factor that plays a role in "seeing".

The following overview offers some examples of units and their values for common situations as observed in practice (all values are approximate)*

---

* Derived in part from Favie et al. (1967) and Boyce (1981).

| Luminous flux | lumen |
|---|---|
| bicycle lamp | 10 lm |
| 'ordinary' light bulb, 150 W | 2,000 lm |
| mercury lamp, 400 W | 21,000 lm |

| Illuminance | lux |
|---|---|
| full moon in a clear sky | 0,25 lux |
| street lighting in a residential street | 1 - 5 lux |
| street lighting on the main road | 10 - 20 lux |
| at sunrise and sunset | 500 lux |
| summer afternoon, under a balcony or in the shade of a tree | 7,500 lux |
| winter afternoon (open field) | 10,000 lux |
| heavily overcast sky on a summer afternoon | 20,000 lux |
| cleare sky on a bright summer afternoon (in the open field, horizontal) | 100,000 lux |

| Luminous intensity | candela |
|---|---|
| car rear light | 4 - 60 cd |
| bicycle headlight (straight ahead - centre of the beam) | 250 cd |
| running lights (straight ahead - centre of the beam) | 400 - 800 cd |
| low-beam headlight in the direction of an oncoming car | 300 cd |
| low-beam headlight in the direction of the pavement | 10,000 cd |
| high-beam headlight (straight ahead - centre of the beam) | 50,000 - 100,000 cd |

| Luminance | candela per m$^2$ | |
|---|---|---|
| asphalt road surface in moonlight of 0.5 lux | 0.01 | cd/m$^2$ |
| concrete road surface at street lighting of 10 lux | 1 | cd/m$^2$ |
| black paper (reflectance factor 4%) at 400 lux | 5 | cd/m2 |
| white paper (reflectance factor 80%) at 400 lux | 100 | cd/m$^2$ |
| grass with overcast sky at 16,000 lux | 300 | cd/m$^2$ |
| grass with clear sky at 100,000 lux | 6,400 | cd/m$^2$ |

APPENDIX 2

Summary SAE DRL-tests (1990)

| DATE | LOCATION | COMMENTS |
|---|---|---|
| JANUARY, 1974 | CHANDLER, ARIZONA | TYPE 1C ROUND, TYPE 2C ROUND UPPER BEAM, TYPE 1A RECTANGULAR UPPER BEAM; REDUCED CD OUTPUT; IDENTIFICATION DISTANCE; GLARE TEST; MIRROR GLARE TEST; EVALUATION OF DRL INTENSITY TO DRIVE AT DUSK; AFTERNOON AND DUSK. |
| OCTOBER, 1982 | OTTAWA, CANADA | BOTH SPECIFIC EUROPEAN DRL AND REDUCED UPPER BEAM; STRAIGHT AHEAD AND PERIPHERAL EVALUATION OF INTENSITY TO IMPROVE CONSPICUITY; DAYTIME, SUNNY. |
| SEPTEMBER, 1984 | DETROIT, MICHIGAN | REDUCED UPPER BEAM; IDENTIFICATION DISTANCE FOR IMPROVED CONSPICUITY; STRAIGHT AHEAD EVALUATION FOR GLARE; PARTIALLY SUNNY. |
| APRIL, 1985 | SCOTTSDALE, ARIZONA | FULL AND REDUCED UPPER BEAM; YELLOW AND WHITE UNIFORM BEAM PATTERN; STRAIGHT AHEAD AND PERIPHERAL EVALUATION AT A SIMULATED INTERSECTION; BRIGHT SUN AND DUSK. |
| OCTOBER, 1985 | INDIANAPOLIS, INDIANA | UPPER BEAM, LOW BEAM, FOG, TURN SIGNAL PATTERN AT SEVERAL INTENSITIES; STRAIGHT AHEAD AND OFFSET; STATIC AND DYNAMIC TESTING; BRIGHT SUN ONLY. |
| APRIL, 1986 | SAN DIEGO, CALIFORNIA | UPPER BEAM, SEVERAL INTENSITIES; TURN SIGNAL, YELLOW AND WHITE; STRAIGHT AHEAD AND OFFSET; STATIC AND DYNAMIC TESTING; BRIGHT SUN ONLY. |
| MAY, 1987 | ORLANDO, FLORIDA | AMBER TURN SIGNAL, REDUCED UPPER BEAM, FULL AND REDUCED LOW BEAM, FOG; SEVERAL INTENSITIES; ALL TESTS WERE STATIC; BRIGHT SUN AND DUSK. |
| OCTOBER, 1988 | KANSAS CITY, MISSOURI | STRAIGHT AHEAD AND OFFSET AT INTERSECTION; CIE DRL BEAM PATTERN; 500 TO 2000CD; BRIGHT SUN AND DUSK. |
| SEPTEMBER 1989 | WASHINGTON, DC | STRAIGHT AHEAD AND OFFSET AT INTERSECTION: 200-7000 CD; ALL WHITE; ALL TESTS WERE STATIC; BRIGHT SUN AND DUSK. |

DATE: JANUARY 29, 1974

SITE: CHANDLER, ARIZONA

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON<br>DUSK: 10 MINUTES BEFORE SUNSET, AT SUNSET, JUST AFTER SUNSET | REDUCED UPPER BEAM; ALL WHITE; 5 3/4" ROUND, TYPE 1 AND TYPE 2 UPPER BEAM FILAMENT; | NO SECONDARY TASKS.<br>A. VEHICLE RECOGNITION DISTANCE, STRAIGHT AHEAD, STATIC, DAYTIME<br>300 cd to 2000 cd | A. 4950 FT. AVERAGE |
| | 300 cd TO 10000 cd | 0 cd | 2100 FT. AVERAGE |
| | | B. ACCEPTABLE GLARE TEST CAR MOVING, OBSERVERS STATIC IN CARS, 6000 cd TO 10000 cd DUSK. | B. 80% ACCEPTED 7800 cd |
| | | C. WILL YOU DRIVE AFTER DUSK WITH DRL LIGHTED? STATIC, 6000 cd AND 8000 cd TYPE 1 UPPER BEAM. | C. 50% OBSERVERS WOULD HAVE TURNED ON REGULAR LOW BEAM BY SIX MINUTES AFTER SUNSET. |
| | | D. IS INSIDE REARVIEW MIRROR GLARE OBJECTIONABLE AT DUSK? 6000 cd AND 8000 cd TYPE 1 UPPER BEAM, TEST CAR 60' BEHIND OBSERVERS, STATIC. | D. 80% ACCEPTED 7700 cd |

DATE: OCTOBER 5, 1982

SITE: OTTAWA, ONTARIO, CANADA

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON 14:30 TO 15:40, CLEAR SKY, NO CLOUDS, SUNNY.<br>FACING NORTH | REDUCED UPPER BEAM, TYPE 2B1; 1000 cd TO 16000 cd.<br>SPECIAL EUROPEAN DRL: 50 cd TO 700 cd. | ALL STATIC 50m TO 400m | |
| | | A. COMPARISON CAR HAD NO LIGHTS OR PARKING LIGHTS OR LOW BEAM OPERATING. | A. OBSERVERS CONSIDERED 100 cd TO BE MORE CONSPICUOUS THAN CAR WITH ZERO OR PARKING LAMPS ON.<br>LOW BEAM MORE CONSPICUOUS THAN DRL INTENSITY 50 cd TO 700 cd. |
| | | B. GLARE EVALUATION, STRAIGHT AHEAD. | B. 1000 cd, NO GLARE BY 88% OF OBSERVERS AT 400m, NO GLARE BY 69% OF OBSERVERS AT 50m.<br>1600 cd, EXCESSIVE GLARE BY 35% of OBSERVERS AT 400m, EXCESSIVE GLARE BY 63.5% OF OBSERVERS AT 50m. |
| | | C. STRAIGHT AHEAD WITH SECONDARY TASK OF TURN SIGNAL FLASHING. 15° AND 30° OFF AXIS AT 50m AND 100m. | C. MOST INTENSITIES (50 cd TO 700 cd) NOT NOTICEABLE AT 15° OFFSET. SLIGHT INCREASE IN NOTICEABILITY AT 30° OFFSET. (PERIPHERAL VISION NOT VERY GOOD) ANY INTENSITY INCREASES CONSPICUITY OVER ZERO. |

DATE: SEPTEMBER 26, 1984

SITE: DETROIT, MICHIGAN

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON 14:05;<br>MOSTLY SUNNY, SOME CLOUDS.<br>TEMPERATURE: 54°F<br>OBSERVERS FACING WEST | UPPER BEAM PATTERN AT REDUCED INTENSITIES.<br>ALL WHITE<br>INTENSITIES: 0 TO 5000 cd. | NO SECONDARY TASKS. | |
| | | A. STATIC TESTING: STRAIGHT AHEAD 0.2 MILE TO 0.9 MILE. | A. 80% OF OBSERVERS COULD CLEARLY SEE 600 cd AT 0.5 MILE, ONLY 24% COULD SEE 200 cd. |
| | | B. DYNAMIC TEST: GLARE EVALUATION DRL CAR DROVE BY OBSERVERS IN ADJACENT LANE WITH DRL AT 5000 cd. | B. NO COMMENTS MADE THAT DRL'S WERE "TOO BRIGHT", "GLARING", OR "BLINDING". |

**DATE:** APRIL 25, 1985

**SITE:** MESA, ARIZONA

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| 14:10 TO 14:30 BRIGHT, SUNNY DAY CLEAR SKY VERY WINDY, OBSERVERS FACED EAST AND NORTH<br>DUSK: BEFORE SUNDOWN 18:25 18:45 SUNDOWN AT 19:05 CLEAR SKY. NOT AS WINDY.<br>OBSERVERS FACED EAST AND NORTH. SUN DIRECTLY BEHIND OBSERVERS | PATTERN 0, 1500, 65000 cd.<br>ALL WHITE FOR TEST A.<br>UNIFORM SIGNAL LAMP BEAM PATTERN 200, 600, 1500 cd. BOTH WHITE AND AMBER. FOR TEST B LAMPS POSITIONED TO POINT TOWARD OBSERVER GROUP AS DISTANCE CHANGED. | OBSERVERS OFFSET 100' BACK FROM CENTERLINE OF ROAD (SIMULATING APPROACHING AN INTERSECTION.)<br>A. TEST WAS FOR PERIPHERAL VISION EVALUATION SECONDARY TASKS OF COUNTING NUMBER OF TURN SIGNAL FLASHES. DISTANCES OF 100', 300', 500'.<br>B. DRL SIGNAL EFFECTIVENESS. DISTANCES OF 100' 300', 500', 800'. | A. DURING DAYTIME MOST OBSERVERS DID NOT SEE FULL UPPER BEAM (65000 cd) OUT OF PERIPHERAL VISION, EVEN AT 100', (45°).<br>AT DUSK, 50% OF OBSERVERS SAW FULL UPPER BEAM AT 100' IN PERIPHERAL VISION.<br>B. DURING DAYTIME 80% OBSERVERS JUDGED 1500 cd TO BE EFFECTIVE AT 150'. ONLY 25% JUDGED 600 cd TO BE EFFECTIVE. NO SIGNIFICANT DIFFERENCE WHITE OR AMBER.<br>AT DUSK, 1500 cd WAS EFFECTIVE AT ALL DISTANCES. 80% OF OBSERVERS JUDGED 600 cd EFFECTIVE AT 300'. |

**DATE:** OCTOBER 2, 1985

**SITE:** INDIANAPOLIS, INDIANA

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON 14:15 TO 15:30 BRIGHT SUNNY DAY, CLEAR BLUE SKY | LOW BEAM 600, 1500, 5000 cd AT H-V.<br>TURN SIGNAL 600 cd AT H-V.<br>FOG LAMP 600, 1500 cd AT H-V.<br>ALL WHITE EXCEPT AMBER TURN SIGNAL. | NO SECONDARY TASK. LAMPS ON EACH SIDE OF CAR WERE LIGHTED. OBSERVERS TO JUDGE MOST EFFECTIVE DRL. LAMPS ALWAYS HAD INTENSITY, SOMETIMES DIFFERENT BEAM PATTERN.<br>A. DYNAMIC TEST. OBSERVERS WERE OFFSET APPROX. 25' FROM CENTERLINE OF PATH OF DRL CAR. OBSERVATIONS MADE 500' TO 250' WHEN DRL CAR WAS DRIVEN AT 30 MPH TOWARD OBSERVERS. DRL CAR ALTERNATED APPROACHING FROM LEFT AND RIGHT.<br>B. STATIC TEST OBSERVER STRAIGHT AHEAD OF DRL CAR AT .45 MILES (APPROX. 2400'). | A. AMBER TURN SIGNAL JUDGED MOST EFFECTIVE AT 600 cd.<br>FOG LAMP JUDGED MOST EFFECTIVE AT 1500 cd.<br>B. AMBER TURN SIGNAL JUDGED MOST EFFECTIVE AT 600 cd.<br>LOW BEAM JUDGED MOST EFFECTIVE AT 1500 cd.<br>WHEN LAMPS ON BOTH SIDES OF VEHICLE WERE EXACTLY THE SAME THERE WAS A SIGNIFICANT BIAS TO JUDGE THE RIGHT LAMP MORE EFFECTIVE. |

**DATE:** APRIL 9, 1986 (PAGE 1 of 2)

**SITE:** SAN DIEGO, CALIFORNIA

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON 14:00 TO 15:30<br>BRIGHT SUNNY DAY.<br>CLEAR BLUE SKY.<br>TEMPERATURE: 67°F | UPPER BEAM: 600, 1500, AND 5000 cd. AT H-V. WHITE<br>TURN SIGNAL: 600 cd AT H-V AMBER AND WHITE.<br>DURING SOME OBSERVATIONS A FLASHING AMBER TURN SIGNAL WAS USED. THEN THE INTENSITY WAS 250 cd. | NO SECONDARY TASK. LAMPS ON EACH SIDE OF CAR WERE LIGHTED. OBSERVERS TO JUDGE MOST EFFECTIVE DRL. LAMPS ALWAYS HAD SAME INTENSITY, SOMETIMES DIFFERENT BEAM PATTERNS. | |
| | | A. DYNAMIC TEST. OBSERVERS WERE OFFSET APPROX. 25' FROM CENTERLINE OF PATH OF DRL CAR. OBSERVATIONS MADE 500' TO 250', WHEN DRL CAR WAS DRIVEN AT 30 MPH TOWARD OBSERVERS. | A. 5000 cd UPPER BEAM JUDGED MOST EFFECTIVE. 600 cd AMBER TURN SIGNAL NEXT. |
| | | B. STATIC TEST OBSERVERS, OFFSET 25' DISTANCE OF 250' AND 500'. | B. 5000 cd UPPER BEAM AND 600 cd AMBER TURN SIGNAL WERE JUDGED MOST EFFECTIVE. |
| | | C. STATIC TEST STRAIGHT AHEAD DISTANCE .3 MILES. | C. 5000 cd AND 1500 cd UPPER BEAM JUDGED TO BE MOST EFFECTIVE. |

**DATE:** APRIL 9, 1986 (PAGE 2 of 2)

**SITE:** SAN DIEGO, CALIFORNIA

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| | | D. STATIC TEST. DISTANCE 500' AND .3 MILES. WILL DRL OVERPOWER A FLASHING AMBER TURN SIGNAL? | D. AT .3 MILES MOST OBSERVERS COULD NOT SEE FLASHING AMBER TURN SIGNAL OF 250 cd FOR ANY REASONABLE DRL INTENSITY.<br>AT 500' 49% OF OBSERVERS COULD SEE 250 cd FLASHING AMBER TURN SIGNAL ADJACENT TO 5000 cd DRL. 80% OF OBSERVER COULD SEE 250 cd FLASHING AMBER TURN SIGNAL ADJACENT TO 2500 cd DRL. |

DATE: MAY 6, 1987

SITE: ORLANDO, FLORIDA

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON 13:35 TO 14:30 BRIGHT SUN, SOME BROKEN CLOUDS TEMPERATURE: 90°F APPROX. 100000 LUX IN BRIGHT SUN. APPROX. 40000 LUX WHEN CLOUDS COVERED THE SUN.<br>DUSK: EVENING BEFORE SUNSET. 18:45 TO 19:35 SUNNY, FEW CLOUDS TEMPERATURE: 80°F APPROX. 18000 LUX AT START OF TEST, 3000 LUX AT END OF TEST. SUNSET AT 20:03 | AMBER TURN SIGNAL,200, 400, 600, cd AT H-V.<br>FOLLOWING LAMPS WHITE: UPPER BEAM 600, 1500, 5000 cd AT H-V. LOW BEAM 75% VOLTAGE AND 100% VOLTAGE FOG LAMP APPROX. 200 cd AT H-V.<br>ZERO INTENSITY. | ALL TESTS STATIC.<br>A. OBSERVERS OFFSET 20' FROM CENTERLINE OF DRL TEST CAR. TEST TO SIMULATE BEING STOPPED AT AN INTERSECTION. SECONDARY TASK OF LOOKING AT ONE CAR AND JUDGING EFFECTIVENESS OF DRL ON A SECOND CAR IN PERIPHERAL VISION.<br>SECONDARY TASK CAR 34' TO 114' DRL CAR 200' TO 500' PERIPHERAL VISION ANGLES 8°, 9°, 24°, 28°.<br>B. OBSERVERS, STRAIGHT AHEAD. NO SECONDARY TASK<br>DISTANCES OF 500' AND 1000'. JUDGE EFFECTIVENESS OF DRL COMPARED TO NO LIGHTS ILLUMINATED. | A. AT SMALLER PERIPHERAL VISION ANGLES (8° and 9°) THE DRL'S WERE JUDGED TO BE MORE EFFECTIVE THAN AT LARGE ANGLES (24° AND 28°).<br>THE DRL'S WERE JUDGED TO BE EFFECTIVE AT SHORTER DISTANCES THAN LARGER DISTANCES. THE FOG LAMP WAS NOT ALWAYS THE LEAST EFFECTIVE DRL.<br>5000 cd UPPER BEAM AND FULL LOW BEAM WERE JUDGED "TOO BRIGHT" BY MORE OBSERVERS THAN ANY OTHER DRL<br>ALL DRL'S TESTED WERE MORE EFFECTIVE THAN ZERO INTENSITY |

DATE: OCTOBER 4, 1988

SITE: KANSAS CITY, MISSOURI

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON 15:35 to 15:57 BRIGHT SUN, CLEAR BLUE SKY. GUSTY WINDS. TEMPERATURE: 52°F OBSERVERS LOOKING SOUTH WEST.<br>DUSK: EARLY EVENING 18:35 TO 18:56.<br>SUNNY AT BEGINNING CLOUDY AT END OF TEST.<br>SUN TOUCHED HORIZON AT END OF TESTS. | CIE TC4.13 BEAM PATTERN 500 cd TO 2000 cd AT H-V. WHITE<br>ZERO INTENSITY | NO SECONDARY TASK. ALL TESTS STATIC.<br>A. OBSERVERS OFFSET AT 20' FROM CENTERLINE OF DRL CAR. DISTANCE 50' TO 500'.<br>B. OBSERVERS STRAIGHT AHEAD.<br>DISTANCES 100' TO 2000'. | A. DAYTIME:<br>2000 cd JUDGED EFFECTIVE BY MORE THAN 90% OF OBSERVERS. 500 cd JUDGED EFFECTIVE BY MORE THAN 70%.<br>DUSK:<br>BOTH CANDLEPOWER LIMITS GIVEN HIGHER EFFECTIVENESS AT DUSK AT ALL DISTANCES.<br>B. DAYTIME.<br>2000 cd JUDGED EFFECTIVE BY MORE THAN 80% OF OBSERVERS AT ALL DISTANCES. 500 cd JUDGED EFFECTIVE BY 7% AT 2000 FT. AND 88% AT 100 FEET. EFFECTIVENESS LINEARLY INCREASES AS DISTANCE GETS CLOSER.<br>DUSK:<br>2000 cd JUDGED EFFECTIVE BY 100% AT ALL DISTANCES. 500 cd JUDGED EFFECTIVE BY MORE THAN 88% OF OBSERVERS AT ALL DISTANCES. |

DATE: SEPTEMBER 26-27, 1989

SITE: WASHINGTON, D.C.

| VIEWING TIMES: DAYTIME, DUSK. AMBIENT CONDITIONS: CLOUDY, SUNNY, TEMPERATURE. | LAMPS AND BEAM PATTERNS USED IN TEST. INTENSITIES, COLORS. | OBSERVATION DISTANCES: SECONDARY TASK; STATIC, DYNAMIC: STRAIGHT AHEAD, OFFSET, PERIPHERAL. | SUMMARY OF RESULTS |
|---|---|---|---|
| DAYTIME: AFTERNOON 15:25 TO 15:45; BROKEN CLOUDS AND BLUE SKY; AMBIENT LIGHT, 20,000 LUX WITH CLOUDS, 55,000 - 77,000 LUX IN SUN. OBSERVERS FACED EAST AND SOUTH. | ONLY WHITE. H-V VALUES OF 200, 400, 500, 1000, 2000, 2400 AND 7000 cd. UNIFORM PATTERN OVER ± 5° ZONE U-D AND L-R. | NO SECONDARY TASK. ALL TESTS STATIC.<br>A. OBSERVERS OFF-SET AT 20' FROM CENTERLINE OF DBL CAR. DISTANCE WAS 200'. | A. ALL INTENSITIES JUDGED EFFECTIVE BY BY MORE THAN 80% OF OBSERVERS, AFTERNOON AND DUSK.<br>B. ACCEPTABLE MAXIMUM VALUE WAS HIGHER IN AFTERNOON THAN AT DUSK. |
| DUSK: 18:48 TO 19:03; SUNDOWN AT 18:58; CLEAR BLUE SKY; AMBIENT LIGHT STARTED AT 1450 LUX AND ENDED AT 280 LUX. OBSERVERS FACED EAST AND SOUTH. |  | B. OBSERVERS STRAIGHT AHEAD. DISTANCE WAS 500'<br>A. AND B. WERE BOTH DONE IN THE AFTERNOON AND AT DUSK. |  |