THE FUNCTION OF ROAD MARKINGS IN RELATION TO DRIVER'S VISUAL NEEDS

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Dr. D.A. Schreuder

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Institute for Road Safety Research SWOV, The Netherlands

SUMMARY

Road markings are part of a system that is introduced to promote safety for the road transportation system. Such a transportation system is understood to be a prerequisite of our present society where production and consumption are far apart so that a large amount of transport is needed - transport of goods, of persons and of information. This transportation system has benefits for society; it has also costs. Part of these costs are essential: construction and operation costs. These costs can never completely be avoided. Another part of the costs is in this sense not essential at all: the costs of accidents, of social and environmental pressure etc. One could perfectly well think of a transportation system where these costs are absent. It is the objective of a road safety policy to reduce these unwanted and unnecessary costs as far as possible. Road markings contribute to reduce accidents and they improve driving comfort.

The extent of the "unsafety" can be found from accident studies. Such studies can also help to find statistical correlations between the accidents and specific parameters in the transport system. In order to find causal relations, however, analytical studies are required. Ideally, such analytical studies would require an accepted and acceptable model of road transport and road safety. Since such a complete model does not exist at present, the analysis is restricted to the driver behaviour (the behaviour of traffic participants as participants). For practical purposes, safety policy is often based on the "three E's" approach (Education, Engineering, Enforcement).

The analytical approach concentrates on the driving task (of car drivers). This task consists of two main task elements: Task I relates to reaching the destination of the trip (following the route), and Task II relates to avoiding accidents when underway. Both tasks are essentially information processing tasks and more in particular decision-making tasks. The decisions are made using the information gathered from the environment. In most cases this information is compared to information that is acquired from the memory. When a decision is reached, actions are performed that ultimately result in movement (or of changes in the movement pattern) of traffic participants or their vehicles.

The decision-making processes related to Task I can be placed in a hierarchical system. The higher levels of this system are related to the socio-economic aspects of the transport system and to the selection of mode of transport and of the route. The lower levels deal with the selection of manoeuvres (complex manoeuvres and elementary manoeuvres) and with vehicle handling. Still lower levels deal with the vehicle operation and can be disregarded here. Task II consists of avoiding danger resulting of sudden unexpected and unwanted incidents. The evasive manoeuvres usually are simple; road markings may offer additional support to perform these manoeuvres as effectively as possible.

A list is constructed of objects that must be visible in order to have adequate traffic (as regards both tasks). For each of this objects it is indicated at which distance they must be visible. In this list of objects, road markings have an important place; they must be visible primarily at distances of some tens of meters. Horizontal road markings are attached to the road surface itself and therefore cannot be seen easily at distances much more than above one hundred meters. This limits the primary area of application of road markings. For larger distances other means are needed to supplement the information provided by the road markings.

The functional requirements for road markings are therefore restricted to the following: they must be visible at distances between some 20 or 30 m, and at least 100 m. They function both for maintaining the course (Task I) and for avoiding emergencies (Task II).

The situations under vehicle head-lamp lighting usually are the most critical. As in vehicle lighting the direction of illumination and the direction of observation nearly co-incide, it is for these conditions that retro-reflecting devices are required. In fact, nearly all road markings are equiped with retro-reflectors.

The functional requirements lead to photometric and geometric requirements: the requirements that must be fulfilled so that the functional requirements can be met. For road markings of the "stripe" or "bar" type the visibility is determined by the (luminance) contrast between marking and road surface. On roads without (overhead) road lighting, that are lit exclusively by vehicle headlamps, the stripes need to show a reflection of at least 0.4 $cd.m^{-2}.lux^{-1}$ (for 100 km/h). The same holds for roads with low quality lighting. For high level lighting installations and for daytime the contrast needs not to be more that than about 10% and 5% respectively. Raised pavement markers are much smaller; their visibility is determined primarily by their luminous intensity. Therefore they are usually equiped with retro-reflecting devices. These devices need to show a reflection of at least 0.006 $cd.lux^{-1}$ (for 100 km/h). This holds for all night-time situations both on lit and on unlit roads. In most cases adequate daytime visibility cannot be ensured, so that raised pavement markers are usually used in combination with stripes.

The geometric requirements are related to the photometric requirements. Road markings that are wide enough, so that the visibility is determined by their contrast, are well above the minimum size to be observed; the size does not need, therefore, to be considered any further. The length of the stripes and their interdistance are not important for the visibility, although they may be important for the recognition. Raised pavement markers are too small to be observed easily in isolation. Therefore they are preferably applied in combination with stripes. When, however, their interdistance is less than 0.60 m, they may be observed as continuous lines.

These aspects deal with the "demand" side of the road transport system: which requirements are needed for the road markings to function. The "supply" side is related to the degree in which the markings perform up to these requirements. The supply side is illustrated in one of the most critical conditions where markings have to perform: at night on roads without public lighting under wet conditions. Here, the accident risk is higher as a result of poor visibility (splash and spray) and of reduced skidding resistance of the surface. The visibility requirements for markings are therefore higher than under less adverse conditions. The actual visibility, however, usually is lower. The only feasible solution is to construct the road markings in such a way that they show near-vertical planes facing the traffic; when they are equiped with retro-reflecting devices the light reflection under vehicle headlamp lighting may be kept sufficient to guarantee adequate visibility.

These considerations lead to a recommendation to the effect that there is a need to design and develop road marking materials or devices that perform equally well under different conditions.

CONTENTS

FOREWORD

The study presented here aims at discussing the fundamental aspects of road marking and their application. The objective of this report is to offer a background on which decisions regarding the development and application of road markings can be based. This background is discussed in considerable detail, keeping in mind those persons or road authorities that have to prepare decisions regarding road markings. In many cases these decisions can be summarised as deciding which type of road marking is particularly suited for different types of roads and traffic situations. These decisions require an extensive study of the background as many different aspects must be taken into account. Road safety and travel (traffic volume) are the most important of these aspects, but also driving comfort and environmental aspects should be mentioned.

As indicated, the report contains a considerable amount of information regarding the fundamental aspects of road marking. In effect, this amount of information and particularly the degree of detail in which this is discussed, is much more than the decision-makers usually will require for the actual decisions. Authorities that prefer to concentrate on the major issues of this subject, may find them in an extensive summary that contains enough detail in order to come to decisions; the actual report offers all the background and the detail on which the summary is based. The report may offer assistance to those engaged in the realisation of the decisions, and to traffic engineers and researchers engaged in road marking.

The report is prepared by dr. D.A. Schreuder of the Department of Strategic Studies of the Institute for Road Safety Research SWOV. Many persons both within SWOV and outside that organisation should be thanked for their support in drafting, preparing and finalising the report.

INTRODUCTION

The scope of the present study is to consider the state of the art regarding driver's behaviour and visual needs for guidance, delineation and information by means of horizontal road markings.
In this respect it is borne in mind that the Commission Internationale de l'Eclairage CIE is at present preparing several reports in this area; it is realised that the different reports should supplement each other as far as possible.

The study should concentrate on the following subjects:

- survey the functions of road markings taking into account the influence of different weather conditions;
- survey the functions of road markings in relation to their day and night visibility;
- survey the functional requirements of road markings as regards the safety aspects for all categories of road users under different conditions of light, weather and traffic for motorways, rural and urban roads;
- survey the possibilities for different types of road-marking materials and products to fulfill these functional requirements particularly taking the European situation into account.

The present report should be considered as a first step, a preliminary study that covers the different questions that may arise when surveying the area of interest. It was agreed in principle that this preliminary study is to be considered as a "pilot study", as a preparation for a long-term effort to cover more in detail the many items involved. It is a matter for further consideration to agree on the more detailed structure of such a future undertaking, both regarding the contents as regarding the organisation and the formal procedures to be followed.

It should be stressed right from the beginning that this report is restricted to the information aspects of road markings. The technology of road markings, the chemical and physical properties of different road marking materials, and the different ways of applying on the road are not discussed in detail. These matters are dealt with comprehensively in the literature. A few surveys may be mentioned here: Adams (1976); Bry (1985); Bryden (1981); Serres (1978); Gillis (1980); OECD (1975); Schönborn & Domhan (1981). See also Goerner (1986).

1. THE ROAD-ACCIDENT SCENE

1.1. Theoretical aspects of road safety

Modern society is a very complicated structure. As many functionally interrelated societal activities are far apart, transport is an essential sub-system of our present society. Transport is to be understood as transport of goods, of persons and of information. The transport of goods and of persons is done in several ways: by road, by rail, and by air and water. Here we will restrict ourselves to the road transport. It is thus to be understood as a sub-system, as a "means" and not as a "goal". Society requires adequate road transport. In order to achieve this, a number of facilities (roads, vehicles, legislation etc.) are provided. This report deals with one of these facilities: the road, and more particularly with one aspect of the road, viz. the road marking, concentrating on their function as a means towards improving road safety.

The road-transport system has benefits: its contribution towards the functioning of society particularly towards the socio-economic aspects of it. It has costs as well: it costs a lot of money to build and to operate a road-transport system. These costs are carried in part by the authorities and in part by the individual traffic participants. These costs, even if they are high, are unavoidable. Other costs are not needed at all to run the system - the damage caused by the transport system. Material damage by accidents and pollution, and immaterial damage (suffering from accidents) and other interference with life. It is a part of the task of road-safety authorities to avoid or at least to diminish this burden. Furtheron it will be indicated that road markings have a function for the road-transport system in both ways: they contribute to the development of transport, and they help to reduce accidents. Furthermore, they may contribute to improving driving comfort.

It is customary to place most emphasis on the second aspect, the reduction of accidents, when discussing road markings. The first aspect, the development of transportation should, however, not be forgotten. A one-sided emphasis on safety might easily lead to the following misconception: it has been shown that road markings will reduce accidents; this improvement, however, is usually offset by a higher driving speed which in its turn could lead to an increase in accidents (see also Sec. 1.3.). The misconception is that the increase in speed is considered as a negative result of road markings because the accidents increase. This, of course, is incorrect: the purpose of roads is to carry traffic as effectively as possible, and an increase in speed will increase this effectiveness. The correct way to tackle this problem is to design a road-marking system that enhances safety and improves the traffic flow without additional accidents. It will be the long-term purpose of this investigation to contribute to this approach. In the first phase, however, the study concentrates on the road-safety contribution of road markings.

When making a decision as to which of several alternatives of road-safety measures should be selected, it is essential to consider their costs and their benefits and to compare them. When measures actually help to reduce accidents, they are effective. If, additionally, the effects (the benefits) of the measures surpass the efforts involved (the costs), the measures are cost-effective or efficient. That alternative which performs optimally should be selected, the one with the best efficiency record. It is not wise to select the most effective of the alternatives, neither to select the cheapest. The costs of road markings are the costs of the material, the costs of application and of maintenance. The benefits are - leaving the throughput aspects apart for a while - the reduction in accidents. This implies that the accidents that happen must be known, as well as the accidents that could be avoided by applying road markings.

1.2. Accident studies

When considering a road-safety measure such as road markings, it is important to know how many accidents could be avoided by applying them. As far as the measure may not yet been executed, one has to rely on estimates. To do this, one might follow two ways: the first is to estimate the expected accidents in the future on the basis of the known accidents that have occured; the second is to make a functional analysis from which one may deduce what could be the contribution of markings to the traffic. Both approaches will be discussed in this report; the first is the accident analysis approach. The second approach is discussed in Sec. 2.1.

Based on the assumption that traffic participation, and the occurrence of accidents in it, follow a specific fixed pattern (i.e. that accidents are not considered as being haphazard, but that they can be described, e.g. by statistical rules) it is possible to estimate the number and type of future accidents on the basis of the past accidents. The method usually applied is the before-and-after type of study. First, the accidents are assessed in the before period; further, the measure is applied and finally - in the after-period - the accidents are assessed again. The difference between the before and the after periods may be attributed to the measure provided that disturbances are adequately accounted for. Disturbances are overall trends in accident occurrance as a result of changes in the overall economic situation, changes in vehicle technology, or the influence of climate and weather. These disturbances and trends can be accounted for by e.g. comparing the results of the before-and-after study with a "control group". Now comes the essential step that is often overlooked: the outcome is considered to be a valid estimation of the results that might be expected if the measure is executed at another moment of time and another location. The difficulties in such studies are obvious: the accidents have to be assessed - a difficult "measurement" with a large "statistical" spread that cannot be avoided; the disturbances can be diminished by applying experimental refinements like e.g. control groups, but they never can be avoided completely; the generalisation (e.g. to other locations) is always questionable and often hardly possible at all. Many of these problems related to statistical accident studies are discussed in detail in the relevant methodological literature. A recent survey is given by Hauer (1986). Finally the largest difficulty: accident studies can never indicate directly the cause of the accidents. So, although one may find that a certain reduction in accidents is correlated to the application of road markings, one can never be sure from this type of study that the reduction is actually caused by the markings. The analytical approach may yield such causal relationships. However, the relevance of such relationships for road safety does not follow directly from it, and must be assessed by accident studies. So in the last instance the two approaches supplement each other.
Notwithstanding these draw-backs, accident studies are widely used in investigations on road safety. More particularly, there is a large body of studies where the road-safety contribution of road markings is assessed.

Anon (1979), CIE (1983), OECD (1975, 1976, 1979) and Schreuder (1985) provide comprehensive surveys of the available material. A specific study on the accident reduction capability of road markings is given in Stimpson et al. (1977) where emphasis in placed on centerlines. In general terms, it has been shown that road markings constitute an effective accident countermeasure. There are differences between different types of marking; it seems that for normal rural roads the most effective are the horizontal markings (striping) at the sides of the road (edge-lines). But centerline markings and delineators in the shoulder are effective as well. There are reasons to believe that conditions of poor visibility contribute considerably to accidents, and that horizontal markings are effective particularly under those conditions (darkness, rain, fog etc.; see e.g. OECD, 1979).
Road markings are often considered as particularly effective to counteract single-vehicle accidents, the accidents where only one traffic participant is involved. This seems logical to assume, as one might suppose that road markings serve primarily to maintain course, and errors in maintaining course usually lead to single-vehicle accidents. Many studies concentrate on these accidents. Now, single accidents are often considered as being related to alcohol usage as well. In this connection, it has been stated that road markings are an effective measure against drinking-and-driving accidents (Jackson, 1981, 1983; O'Hanlon, 1983; Schreuder, 1983, 1983a).

1.3. Risk homeostasis

It is well-known from daily life that, when a safety measure is introduced, drivers tend to accept taking more risks: most - or maybe all - safety measures are to a certain degree counteracted by an increase in risk taking. Based on this idea, the theory of the risk homeostasis has been developed. In its most extreme form it has been described by its main protagonist Wilde as follows: each individual road user selects a certain degree of danger; this can be expressed in a number of accidents to be experienced per vehicle-kilometer or time unit. Now all safety measures are counteracted by each individual road user in such a way that this degree of danger does not change. This was expressed as follows: "The theory posits that the traffic accident rate per time unit of exposure is the output of a closed-loop control process in which the target level of risk operates as the unique reference variable. Thus time-averaged accident risk ultimately depends upon the level of risk accepted in return for the benefits received from mobility" (adapted from Wilde, 1984, p. 292).

With such an extremes, the theory is not very convincing, because it is clear from practice some safety measures help and others do not. Further, it is difficult to visualise in which way individual road users are able to estimate their accident involvement with sufficient accuracy, taking into account the well-known fact that human beings are notoriously poor in estimating small probabilities. The theory seems, however, to have its merits when considered at a large scale for the prediction of average values, but not for the prediction of individual accidents. With this proviso, many studies have been made at a number of research establishments in the USA, in the UK, in France, Germany and Japan. As most of this research is still in progress, it is not possible to come to a conclusion regarding the final value of the risk-homeostasis theory for road-safety studies. One of the institutions where research of this type is undertaken, is the Institute for Perception IZF-TNO at Soesterberg in the Netherlands where specific emphasis is put on the relevance of this theory to the application of (horizontal) road markings. Several of these studies will be quoted in chapters where course holding and where the visibility aspects of road markings is discussed. See e.g. Blaauw (1984); Blaauw & Padmos (1979, 1981, 1982); Blaauw et al. (1983, 1984); Godthelp (1984); Godthelp & Riemersma (1982, 1982a); Janssen (1984); Janssen & Van der Horst (1980); Padmos (1984); Riemersma (1979, 1979a, 1983); Van Norren (1981), Walraven (1980).

Sometimes, the risk-homeostasis theory is misused. An example, relevant for the study of road markings, is the following. The theory postulated that the driver requires a specific risk level. If the present level is lower, the driver will increase his driving speed until the level he perceives equals the level he requires.
Now, the driving speed is of considerable importance for the efficiency of the transport system - in other words, driving fast is more efficient than driving slowly. When, however, one disregards the primordial func-

tion of traffic - to have a means of transport of goods and persons for the benefit of society at large - one could easily be led to believe that driving faster is only driving more dangerously. And furthermore the speed is about the only aspect of driving that can easily be noted from an observer at the road-side. This misconception, that is the result of a "one-track-minded" way of looking at the transport system, and of an erroneous application of the risk-homeostasis theory might lead to dubious decisions like the one proposed in France many years ago: one should delete the expensive road markings since they only led to higher speeds, causing as many additional accidents as were saved by the markings in the first place (Frybourg, 1972). It was pointed out already that this is not the correct way to regard road markings; it should be stressed, however, that it is essential to avoid the additional increase in accidents! (see Sec. 1.2).

1.4. Theory of accident causation

At present, the theoretical framework for of accident causation is still incomplete. Apart from global considerations based on general ethical concepts, most theories available at present are restricted to limited aspects of road safety.

Assuming a certain analogy with public health considerations, for practical applications often the idea is presented that the traffic is essentially a "healthy" affair, and that accidents represents those cases where this "healthy" affair breaks down. According to the analogy, a precise definition of "healthy" is not given - and not required; it is sufficient to indicate that "healthy" implies the absence of unwanted symtoms and effects, in this specific case the absence of accidents. The reason for this break-down of the system is considered to be either a lack of information or of skills from the part of the traffic participant, or the absence of the right "mentality". In Sec. 1.6 a few remarks are made regarding the psychological aspects of this; here it is sufficient to state that this approach proves to be applicable for practical situations, more specifically for the establishment of an overall road safety policy.
When elaborating this theory, it is usually realised that the transport

system consists of three elements, viz: the road, the vehicle and the operators (the drivers). Sometimes the environment is added as a fourth element. Technology provides the means of transportation (roads and vehicles), whereas the drivers may use the system correctly - or not, thereby causing accidents. Thus, the human factors aspect of road safety include the skills and attitude of the drivers, and the means to assist or to force the drivers to act correctly. More recently, it is realised that the authorities play a decisive part in the traffic system, as planners, as constructors and as operators of the system. Finally, at present emphasis is placed on the decision-making aspects in the road traffic safety system as well. Further details of this are given in Sec. 1.6.

1.5. Road safety policy

Road accidents constitute a major cost aspects of the transportation system. As an example, the total monetary damage as a result of road accidents in The Netherlands is estimated a being more than Hfl. 10,000 mio (Anon, 1985) in the UK more than £ 2,500 mio (Mackaulay, 1986). These values are not completely comparable as different criteria are used in the two countries. To this the non-monetary damage must be added. Sabey (1980) quoted simular values for 1977: monetary losses amounted in the UK to £ 946 mio, non-monetary costs ("pain, grief and suffering") to £ 347 mio, giving a total of £ 1,293 mio. Emde et al. (1985) gives similar values for Germany; these values are split up per accident: 1,200,000 DM for a fatality, 54,000 DM for a serious injury and 4,100 DM for a light injury. Obvisously, such costs make a road policy an urgent necessity.

Road safety policies can be based on the three aspects indicated above (Sec. 1.4). They are traditionally indicated as the Three E's:
- Education
- Engineering
- Enforcement.

Education includes driver instruction and training, and providing information to the general public or to specific high-risk groups etc. One might include here as well the information to traffic participants re-

garding the route to be followed or regarding the actual state of a particular stretch of road. Road markings may play a role in systems for the transfer of such information.
Engineering is a very wide area which includes the road, the vehicle and the transport system in general. Obviously, road markings fit mostly into the area of Engineering. One should be careful, however, not to conclude from this that all factors and problems of road markings are related to engineering problems, and that therefore they should be solved by engineers. It is one of the main objectives of this report to suggest a more wide approach to road marking problems.
Enforcement, finally, is more related to the activities of the law enforcing agencies; they touch only lightly to problems of road markings.

In the past, measures based on each one of these "three E's" were studied, considered and introduced in isolation. Many of these measures have clearly been effective, but in some cases the problems were not solved. Further refinements of the measures could sometimes lead to some improvement; considerations (a.o. based on the theoretical studies of the type described in Sec. 1.6 and 2.1) suggested that a considerable additional reduction in accidents did require another approach, an approach where the different measures were not designed and applied in isolation, but were incorporated in an integrated road-safety policy. This process and its results is clearly described in OECD (1984). For the subject of this study this implies that the design and application of road markings should not be considered in isolation, but must be integrated in a general road-safety approach. In effect, this implies that the "three E's" are applied together, taking into account their mutual dependence and their interactions. Examples of this approach may be found in Chapter 6 where the wet-night visibility of markings is discussed.
The Three E approach is based essentially on a rather restricted idea of accident causation. This is not only a matter of scientific interest: one may encounter occasions where quite promising road-safety measures simply do not work because the idea of an essentially "healthy" affair that sometimes breaks down, is an oversimplification. It is beyond the scope of this report to discuss these things in detail or to develop here a more complete theory; it seems, however, useful to devote a few words to several of the psychological aspects involved.

1.6. Aspects of traffic psychology

Traffic is an abstraction; in reality one has to deal with an aggregate of a number of individual traffic participants all of which react on their own according to their own needs and possibilities. Furthermore, the individual participants react to each other - they interact. In order that a theory of traffic participation or of road safety can be applied to the questions that may arise in practical experience or in theoretical investigations, it must be able to deal with these different actions, reactions and interactions. In other words, successful theories on traffic and on road safety must be based on psychological premisses. Here, a considerable gap in scientific knowledge presents itself.

Psychological considerations of the actions of traffic participant should start with the motivational aspects of this participation. Now, the prevalent theories of human motivation are not very helpful. Although the times of strict behaviourism, where no other motives than conditioned reflexes and biological homeostasis were acknowledged, seem to be over, the theories that permit to deal with more complicated human activities, particularly the "higher" activities and inspirations are only beginning to involve. A framework is proposed by Schreuder (1973) where emphasis is placed on motivational aspects of car driving related to the trip itself, the status of vehicles, the influence of role taking in the social context, and the influence of agression. As regards road safety there is however no theory or model which can accomodate factors like careful driving, neither aspects like the mentality indicated earlier. As an example, it is unknown why alcohol in small doses, that improves ("lubricates") most human interactions, is a deadly peril on the road. In a similar way, only little is known of the influence of factors like attention, vigilance, fatigue etc. (Michon, 1979).

The different aspects of transport psychology and their counterparts of social psychology and sociology will not be discussed in this report. It is sufficient here to note a consider of basic knowledge in areas of purely psychological nature, notably regarding the motivation of human beings to act like they do. They seem to be essential to understand better the factors indicated above: vigilance, fatigue etc. It is likely that the specific benefits of road markings are to help drivers (and other traffic participants) to perform adequately in traffic, especially when they face problems related to (lack of) vigilance or to fatigue. In short, without an adequate theoretical framework it is difficult to indicate why road markings improve road safety in the first place, and furthermore how the design of road marking materials can be improved so they perform better.

After the motivation, a second important psychological concept is the concept of decision. A decision is defined as the outcome of a decision-making process. Decisions are made on the basis of information acquired from the environment in conjunction with the contents of the memory (that may be understood as a data bank of results of earlier information acquisition); they lead to actions. Thus, they may be inserted between the "Stimulus" and the "Response" of classical behaviourism, yielding a S-->d-->D-->R process (where d designates the decision-making process and D the decision). In modern cognitive psychology these concepts are discussed in detail; it is, however, still premature at present to apply the results of this research directly to practice. These modern developments are described in detail in Michon et al. (eds.) (1979); see also Schreuder (1985a, b).

In the following chapter we will discuss an approach towards better understanding traffic participation; this approach is based on the analysis of the "driving task"; it is mainly an empirical approach that is based to a certain extent on the decision concept described earlier. This approach will be followed, but that does not imply that further fundamental research on the basic psychological questions should be neglected! Furthermore, this approach involving the analysis of the driving task constitutes the alternative approach to accident analyses, as indicated in Sec. 1.2.

1.7. Conclusions

- The road-transport system is part of the societal structure. Road markings offer a means to improve the function of the road-transport system.

- The benefits of the road-transport system are in the improvement of the societal structure, particularly in the socio-economic aspects. The costs include a.o. road accidents.
- Road markings contribute to the develoment of transport, they help to reduce accidents and they may improve driving comfort.
- Two methods are available for studying the safety benefits of road markings: accident studies and functional analyses.
- Accident studies have shown that road markings may contribute considerably to the reduction of road accidents.
- Studies suggested that the application of road markings occasionally resulted in increasing driving speed. This is to be considered as a (travel) benefit. Presently, a comprehensive accident causation theory is still lacking. For practical purposes, the "three E's" approach yields interesting results (Education, Engineering, Enforcement).
- For a further development of the theory of accident causation, further psychological study is urgently required, particularly focussing on aspects of driver motivation and of decision-making processes.

2. THE THEORY OF TRAFFIC PARTICIPATION

2.1. The driving task

This section deals with individual traffic participants both viewed upon separately as well as in their interactions. First, the terms "driver" and "traffic participant" will be clarified. Obviously there are other persons that participate in traffic than drivers (of cars) alone. However, practice did show that most severe problems, regarding road accidents, are related to drivers of cars. Therefore the word is used generaly, but is should read in many cases "traffic participant", particularly when dealing with victims of accidents, who in many cases are not drivers at all. The word "driver" will be used throughout this report signifying riders and pedestrians as well.

Driving a car is hardly ever a goal as such. Nearly always it is a means to reach a goal - literaly the end of the journey, or figuratively the "goal" of the journey as expressed in socio-economic terms. These might include the delivery of goods, the attendance at meetings, or the visit to relatives or friends. In order to reach the destination of the trip, two things are necessary: firstly the destination must be reached - the correct route should be taken - and secondly one must avoid incidents that might lead to collisions (accidents) on the way. These two aims constitute the two major aspects of the driving task. They are very important and therefore they will be designated as Task I and Task II respectively. Task I is selecting and following the route, Task II is avoiding collisions. Details are given by Schreuder (1984, 1984a, 1985a, b).

The two tasks differ in several ways. Task I is in fact a rather complicated one. Essentially, it is a decision-making process - to decide which route should be taken etc. In fact, Task I can be described as a series of decision-making processes that can be grouped in an hierarchical structure. Each of these decisions is made on the basis of information extracted from the environment, while taking into account contributions from the central agency (the memory). Decisions lead to activities. This is the traditional model of decision-making processes (Broadbent, 1958; Michon, 1979; Vlek & Wagenaar, 1979).

The hierarchical structure contains decision-making processes in different levels; in each level the "end" and the "means" of the decision may be indicated. The "means" at a certain level n constitutes the "end" at a lower level n-1; and the "end" at level n is the "means" at level n+1. The structure is a very large one, consisting of a large number of levels, one over the other. However, only a few are relevant for the driving task:

- the selection of the route;
- the selection of the manoeuvres;
- the selection of the vehicle-handling actions.

Over and above these, one may discern decisions regarding the selection of the mode of transport, of the destination, of the socio-economic goals etc. And below it, one finds levels that deal with the actual operation of the steering, brakes etc. Another aspect of Task I is the fact that the activities serve a purpose; even if they are not the result of a completely conscious and rational decision-making process, they are "wanted"; they offer some sort of reward, and therefore they are related to positive motivation.

Task II is different. Primarily, Task II consist of manoeuvres that are needed to avoid incidents, particularly those that may lead to collisions: it is coping with emergencies. This means that usually there is no time for well-balanced decisions. Avoiding collisions usually involves the most simple manoeuvres. In terms of the levels indicated above, they all take place on the lowest level of actual vehicle handling (swerving, braking etc.). Also the motivational aspects are different: emergencies are "unwanted"; they interfere with earlier plans and decisions, and require an adaptation of them. So they make the road towards the reward longer (Schreuder, 1985b).

In spite of the fact that Task II and the lower level of Task I are very similar, one should expect a considerable difference in the way the two tasks are performed; this implies also a considerable difference in the quality of the information that is provided for the driver - or which must be provided (Schreuder, 1985a, b).

2.2. The phase-model

On the basis of the hierarchical structure of the decision-making processes as indicated above, one may construct a phase-model for different accident types and for different accident countermeasures. In this respect, it seems useful to include the "higher" levels of the decision-making processes as well, because many accidents would be avoided, or be different, if other decisions would have been made regarding the selection of the destination of the trip or of the mode of transport. Furthermore, when discussing road-safety measures it is not enough to consider the individual traffic participants and their interactions; it is necessary to take the "sum aspects" into account as well, that a.o. can describe traffic streams. They constitute the area where measures of road-safety policy usually are active: traffic engineering, but also legislation and enforcement (see Asmussen, 1972, 1974; OECD, 1972; Schreuder, 1974; Asmussen & Kranenburg, 1982; see also OECD, 1984).

The phase-model presents a description of the consequences of system deficiences in different levels and in different phases of the decision-making processes. On levels of the selection of manoeuvres and of vehicle handling the first major cause for system faults are found in the input of information. Furthermore, the decisions themselves may be inadequate or incorrect and finally the actions may be inadequate. But also on this level the contribution of the memory is extremely important: the memory contribution makes all the difference between expected and unexpected situations, as it is in the memory that all experience and training is located. It has been shown repeatedly that the degree in which a situation conforms to the pattern of expectation is of the greatest importance so that the most appropriate decision will be made. One might say that experience and training (the memory contribution) shifts situations from the area of Task II towards the area of Task I: from emergencies towards expected factors.

Finally phase-models permit to make a distinction between the tasks of the road authorities and those of the individual drivers. It will be clear that, although they both are decision-making processes, they are very different indeed; and also that both are very much relevant for road markings.

2.3. The manoeuvres

In Sec. 2.1 three levels of decision-making processes were introduced that seem to particularly important for the driving task, viz: route selection, manoeuvre selection and vehicle handling.

The highest of the three is the level of the selection of the route. This level consists primarily of decisions that are made consciously and to a large degree on a rational basis. Furthermore, the decision-making process is mainly of a cognitive nature. And finally the information that is gathered from the environment is mainly coded into symbols (letters included). Although this area is of the greatest importance for road traffic it has little relevance for road markings; for our report the lower two levels are more important.

The second level is the level of the manoeuvres. The discussion of the manoeuvres is based on considerations introduced by Schreuder (1974). In this, the term "manoeuvre" signifies the actions performed by the driver. Both on practical and on theoretical grounds, manoeuvres will be subdivided into "elementary manoeuvres" and "complex manoeuvres"; the second group consists of compounds of the first. The practical reason for this subdivision is that the elementary manoeuvres are just the elements from which all other manoeuvres can be constructed. The theoretical reason is that elementary manoeuvres, while forming the smallest parts of conscious decisions in driving, are the highest that can be learned in such a way that they can be performed automatically. Elementary manoeuvres can become conditioned reflexes, but complex manoeuvres cannot. In fact, driver training can be understood as transforming the performance of elementary manoeuvres from conscious decisions towards conditioned (i.e. unconscious) reflexes.

The number of different elementary manoeuvres is only small. In fact one may distinguish only four (five if one includes "just going on" as a separate manoeuvre on the basis that this action may be the result of a decision-making process as well), see Table I.

Each of these actions (or manoeuvres) does require a different level and type of information. This will be discussed in the next chapter (Sec. 3.4.). It may be noted that "negotiating curves" is not listed here; this manoeuvre belongs to the complex manoeuvres.
Contrary to the number of the elementary manoeuvres, the number of complex manoeuvres is much larger. Furthermore, the description (the definition) of them is more ambigious. In Schreuder (1974) a preliminary list is given. Further investigations are in progress. One of the difficulties is the fact that it depends on the traffic situation on the driver which of the complex manoeuvres might be relevant. Here only a few of the manoeuvres will be discussed, particularly those relevant for the discussion of the functional and optical requirements for road markings. Apart from the manoeuvres "just going on" (a complex manoeuvre as well!) and "negotiating curves" these include "overtaking and passing (in the presence of opposing traffic)" and "crossing (priority) intersections". The complete list as set up by Schreuder (1974) is given in Table I. The relevance for the present study may be demonstrated by the fact that road markings are effective in assisting drivers to negotiate curves in a correct way, particularly inexperienced drivers or drivers that are tired or inattentive.

The third level (below that of the elementary manoeuvres) is the level of the vehicle handling. This aspect can be regarded as well as the outcome of a decision-making process - be it that the selection of the appropriate actions usually is quite straight-foreward. However, even if they are simple they are really true decisions according to the definition given in Sec. 1.6. The decisions are related to the selection of the position on the road - more precisely the selection of the lateral position and the changes in the longitudinal position. In other words the position in the traffic lane and the speed. They can be indicated conventionally by y and $\dot{x}$ where x is the coordinate in the direction of travel (the lengthwise coordinate) and y the cross-wise coordinate (see e.g. Schreuder, 1984).

The lateral position is selected on grounds of both Task I and II; when the discrepancy between the selected value and the actual (perceived) value is too great, a steering-wheel movement will be made in order to correct that. The steering-wheel movement is in a direction contrary to the direction of the discrepancy, and usually its magnitude is proportional to the discrepancy. This is obviously a case of the traditional "control" (Schreuder, 1985e). The actions will be made mostly without a fully conscious decision; again here training and experience reduce the amount of conscious decision making.

As regards the foreward speed we may meet two distinct possibilities. First an empty road. Here the speed is selected according to criteria depending on safety and time consumption, with legal speed limits and the characteristics of the vehicle as limiting factors. Second the case of preceeding traffic. Now the speed hardly can be different from that of the preceeding car. It should be kept in mind that according to the definitions, changing speed in order to keep the distance to the foregoing car constant is considered as being an elementary manoeuvre, whereas the decision to overtake and pass that proceeding vehicle is a complex manoeuvre.

2.4. Traffic as a decision making task; traffic policy

The phase-model as described in Sec. 2.2. enables to distinguish between the decision to be made by authorities and by traffic participants. The decisions of the authorities are related primarily to the set-up and operation of the traffic facilities, and to the legislation and enforcement. These decisions interfere to a large extent with the decision-making process of the individual traffic participant. The decisions of the authorities constitute the limiting factors for the possibilities for the traffic participants to select their manoeuvres. The decisions of the authorities usually involve a considerable amount of money; the cost/-effectiveness (the efficiency) of the measures is of great, and often of crucial importance. In this respect it is essential that the authorities have the best tools at their disposal in order to come to the best decisions.

From Sec. 1.4. it will be clear what may be those tools: they relate to engineering and enforcement measures. The engineering includes the selection of the best road-marking materials as regards their overall performance judged according to their cost/effectiveness, the best ways to apply them, but also methods for testing them and also considerations of national and international standardization and harmonisation - of the materials, of the equipment, and of the measuring and testing procedures. Enforcement measures might include the regulations that have to be followed by local road authorities, regarding e.g. application and maintenance of road markings.

It is one of the objectives of the present study to assist the authorities to make the best use of the available "tools". For this, information is made available related to current road marking materials and applications, on future developments, with the aim to present criteria to judge the quality of these "tools" and to evaluate them - the tools being the horizontal road markings.

2.5. Conclusions

- The traffic task of drivers (and of other traffic participants) can be divided in two aspects:
Task I is selecting and following the route, Task II is avoiding incidents that might lead to collisions.
- The tasks consist of decision-making processes that may be included in an hierarchical structure.
- When considering Task I, three levels from this hierarchical structure are most important:
  - the selection of the route;
  - the selection of the manoeuvres;
  - the selection of the vehicle-handling actions.
- Task II consists of coping with emergencies.
- The different aspects of accident occurrence may be combined in a "phase-model".
- Manoeuvres consists the most important level when considering road markings. Two sub-levels may be discerned:
  - elementary manoeuvres;
  - complex manoeuvres.

In both cases, preliminary listing of manoeuvres are available.

- The vehicle-handling level is related to the lengthwise and crosswise position on the roads, and the changes therein (speed and lateral position etc).
- The phase-model permits to discribe the decision-making processes that constitute the traffic policy; it permits to indicate where road authorities can be assisted in selecting the optimal road markings.

3. INFORMATION NEEDS

3.1. Visual information

In road traffic the decisions are made on line and in situ by the traffic participants. These decisions are made on the basis of information, the majority of which is, again on line and in real time, collected from the environment. This information is combined in most decision processes with other information that is deduced from the central agency - the memory. In this, the term information is used as in the traditional McKay-Shannon information theory (Shannon & Weaver, 1949; Wiener, 1948, 1954).

In more practical terms, the information is always about something. This "something" will be indicated here with the term "object" in the original meaning of the word: the object of observation. Furthermore, practice indicates as well that the information at the manoeuvre and vehicle handling levels is nearly exclusively of visual nature, i.e. the information is collected and processed by the visual system. A figure of 95% visual information is often quoted; as "information" is not defined precisely, this figure is primarily to be seen as an order of magnitude; see e.g. Allen (1970); Gramberg-Danielsen (1967); Böcher (1975); Michon (1979); Jonkers (1986); Moon (1961). Auditory and kinesthetic information, however, is very important in the operation of the vehicle: that is in the level "below" the level we indicated as "vehicle handling". It might be added here that kinestethic and to a lesser degree the auditory information are the basic idea behind the concept of the "rumble-strip": vibration and noise should warn inattentive drivers that they were close to leaving the road (Capelli, 1973; Farrimond, 1968; Schreuder, 1980, 1981a, Visser, 1977). It might seem to be ironical that such markings that additionally proved to have excellent wet-night visibility properties are applied only in restricted circumstances as the result of the additional noise that sometimes is considered as being disturbing (Anon, 1985a; Schreuder, 1985).

The acquisition and processing of visual information is usually termed as (visual) observation. When an object is seen (is observed visually) it is a said to be "visible"; the criterion is visibility. Visible means that the object under consideration is just observable or detectable. It is said to be at the visual threshold. This visual threshold is established by means of special experiments that have to take place in the laboratory under ideal standardized and regulated conditions. These conditions also pertain to the observer: the threshold of visibility is always related to a "standard" observer (see Schreuder, 1985c). Notwithstanding the great importance for fundamental research, such visual thresholds have only little direct relevance for practical traffic situations (Blackwell, 1946; CIE, 1972, 1981; Middleton, 1952).

Usually, (visual) "objects" do not present themselves in isolation. In practice, usually a large number of objects present themselves simultaneously. The object that is relevant for the traffic situation under consideration must therefore compete with these other objects. The degree in which this competition is successful, is expressed in the conspicuity of the object, signifying the degree in which it "stands out" in respect to the other objects.

Visibility is necessary and conspicuity is favourable for adequate (i.e. useful) observation. It is, however, not enough. In order to be able to use the information acquired from the object in the decision processes it is necessary to know more about the object: one must know what it is, whether it belongs to a category of objects that is relevant under the circumstances and for the decision-making process under consideration. In short, one must be able to recognise the object: to be able to classify it in the correct way. This, of course, presupposes that the observer is aware of that particular class of objects. Recognition is therefore a comparison of the information acquired from the environment to the information available already in the memory. One of the consequences of this is that although visibility and conspicuity may be regarded as characteristics of certain types of objects, recognisability cannot be so, as it involves essentially the (memory of) the observer. This means as well that recognisability cannot be regarded as an above-threshold characteristic of the object. This in contrast to the conspicuity, that can be expressed in supra-threshold terms. In most cases, the conspicuity of a specific object can be assessed simply by taking the threshold value of visibility (the detectability as found from laboratory experiments) and multiply this with a factor, usually termed the "field factor"; see e.g. Blackwell, 1956; CIE, 1981; Douglas & Booker, 1977. When comparing conspicuity and recognition, one must take the contribution of the observer towards the latter into account (Schreuder, 1986c).

In the past, when considering the visual observation in traffic one restricted the considerations to the threshold conditions to visibility. For some situations and for some visual tasks this may have some significance e.g. in maritime transport but not for road traffic. Still, in many cases one tries to base the assessment of practical road-safety measures on visibility studies like the monumental studies of Blackwell (see CIE, 1981). These studies are really oustanding in quality and scope, but they have restricted direct relevance to road traffic. The reason for this is not primarily as Vos & Padmos (1979) did believe, the lack of accuracy, but rather the fact that participating in traffic and particularly of driving a car in traffic is primarily a decision-making task and NOT primarily a visual-detection type of task (Schreuder, 1980a). Putting emphasis on conspicuity as proposed by Schreuder (1970, 1977) in the "functional approach" offered some improvement. However, further consideration of traffic with emphasis on complicated situations did make it clear that it is necessary to take one step further, beyond the conspicuity and to concentrate on the recognition. These considerations were involved in the decision to make wheel-shaped side reflectors obligatory for pedal bicycles in the Netherlands; see Blokpoel et al., 1982; Schreuder, 1984b.

A further and more far-reaching example of this was found when studying complicated and difficult traffic situations like the decisions to be made about giving priority to certain classes of road users (e.g. motor cycles) and not to other (e.g. pedal bicycles and mopeds) at night under poor public lighting and in dense traffic. Threshold values of detection did not have any meaning at all; placing emphasis on the conspicuity did not improve the situation as it lead only to a competition in respect to conspicuity between different classes of traffic participants and between individuals within the classes. The end result was likely to be a deterioration of the road safety in stead of an improvement (Ebell et al., 1984; Ebell-Vonk et al., 1983; IWACC, 1983, 1983a; Schreuder, 1983, 1985c; Welleman, 1983, 1986; Noordzij et al., 1985; Tenkink, 1985; SVT, 1985). In general, however, raising the conspicuity is usually good road safety policy, as in this way the attention of the driver/observer may be drawn and directed toward the objects to be observed.

It is not simple to indicate in general terms what are the consequences of putting emphasis on recognition in stead of on conspicuity. The first aspect is that the shape becomes a predominant issue but it cannot be indicated what detailed aspects of shape. This is the result of the fact that recognition is essentially a form of collaboration (symbiosis) between object and observer. A second aspect is related to the time that is required for adequate observation: recognition is a more complex process than simple detection. One might expect therefore that more time is required. As the observer again is involved, and particularly his motivation, his vigilance and his experience, one might expect in some cases a very long extra time, but in other cases hardly any extra time depending on the circumstances and on the observer; particularly if the circumstances are well-known to the observer - if there are no unknown and/or unexpected aspects in these circumstances. Again, as the memory plays a crucial role it is primarily a matter of expectation; in other words whether the situation refers to Task I or Task II (Sec. 2.1.). It seems safe, however, to allow for more time. This is obviously important for the determination of the distance from which specific objects must be "visible" (here: must be recognised). This distance, usually referred to as stopping distance, is discussed in the next section.

3.2. The stopping distance

The processing of information requires time, often a quite considerable time. This will be clear from the foregoing discussions where we indicated that the processing of information consists of a sequence of actions that follow one after the other. When discussing visibility in road traffic, particularly the visibility requirements of road markings, obviously it is necessary to know this time. It is at the present state of knowledge not possible to indicate precisely the time interval that is needed; it will be clear, however, that there will be a considerable difference in the time requirements for the different manoeuvres, and that this time depends to a considerable degree on the question whether the object is expected and known, or not (whether one has to consider Task I or Task II).

Traditionally the required time is considered to consist of only two aspects: the time for the driver to react, and the time needed to stop the vehicle. Obviously, this is an oversimplification that furthermore is applicable for only one manoeuvre: stopping. A further simplification is usually introduced: the reaction time is considered to be a constant determined primarily by the need to arouse the driver (Schrecksekunde in German) and is taken to be one second in time. Details of the reaction time that really is a complex phenomenon, may be found in Sanders, 1979. Furthermore, it is assumed that the driver makes an emergency stop with full brakes. This implies a high value of the retardation; it is customary to take values around 5 m/s^2. The resulting values of the total required time is short - for most conditions not realistic at all.

It is well known from psychological studies that the reaction time depends considerably on the degree in which the objects to be reacted upon are known and expected under the prevailing circumstances (see Sec 3.1). Furthermore, the degree of arousal is important in the length of the reaction time; this implies that factors that influence the arousal are important as well (fatigue, drugs, alcohol etc.). And finally there seems to be an influence of the motivation. The resulting overall "reaction time" may be somewhere between 0.2 s for some very specific laboratory tasks and ten seconds or more for situations were complicated decisions have to be made.

The overall reaction time consists of several elements. First, the time interval needed for the visual detection. As was indicated earlier (Sec. 3.1) this can be already a fairly complicated affair, particularly when recognition is an important factor. Second, there is a time interval in which the selection is made between different alternative courses of action. One might suppose that this interval is longer for complicated situations where several alternatives are present. It seems therefore that this interval is larger for complex manoeuvres than for elementary manoeuvres or for vehicle handling actions. Third, the interval needed to make the actual decision. For cognitive processes like the decision which of alternative routes to take, this time interval may be quite large. At the other hand, for decisions that are more like conditioned reflexes, the time may be very short indeed. And finally the overall reaction time includes as well the time interval to really start the manoeuvre that was selected. This may take at least one second for braking as the foot has to taken away from the accelerator and placed on the brake pedal; the force has to be applied and the hydraulic pressure has to built up before the actual braking can begin. For other manoeuvres the time might be shorter. As regards the detection of road markings, it is customary to take an overall reaction time of some 5 seconds (Schreuder, 1981). This value is based a.o. on measurements of Weir & McRuer (1967) who found a minimum value of 5 s for efficient, anticipatory steering behaviour and of Allen et al. (1977) who found 3-4 s in a delineation study in adverse weather. Sometimes a shorter time is used (3 s; CIE, 1985).

For emergency stops it is usually assumed that the retardation is about 5 m/s^2. In most countries this is the minimum requirement for passenger cars (Schreuder, 1981). On very good, rough, dry roads and with good tires, a well maintained and new vehicle may reach up to 7 m/s^2. However, ordinary cars on ordinary roads (that may be wet) the maximum retardation of is often not more than some 3 to 4 m/s^2 (incidently, the earlier minimum legal requirements for cars were "only" 3,85 m/s^2, the current value for lorries). All this relates to an emergency stop. In normal traffic such stops are very infrequent and usually result in multiple collisions as the following vehicles often cannot avoid a preceeding vehicle that is stopping in such a way. When discussing the minimum requirements for vehicle-braking systems this is acceptable and may be even necessary; for the discussion of visibility of objects in normal traffic this sort of values for the retardation are not relevant. There is, however, only very little research on the numerical values of the retardations that correspond with normal braking in normal traffic. Schreuder (1981) compiled some data, from which follows that in normal traffic one has to reckon with retardations between 1 and 3 m/s^2; the lower value represents "coasting": just taking the foot off the accelerator, and the higher value represents fairly strong braking (where loose papers will slide off the seats); Mortimer, 1971; Schreuder, 1981.

The stopping time is influenced to a very large extend by the driving speed, the distance needed to stop (the stopping distance) in even a larger way. In Table IIa data of the stopping distance are given for different values of the overall reaction time, of the retardation and of the driving speed. It is obvious that the traditional values are very short indeed; it seems to be unwise to base any road-safety measures on such unrealistic values. Practical values such as quoted by Baerwald (1965) are added, see Table IIb.

3.3. The preview

The discussion above was concentrated on the manoeuvres "stopping". As indicated in Sec. 2.3 this is only one of the many manoeuvres with which drivers may be confronted. Most of them require a shorter distance, or a shorter time.
In all cases the relevant objects have to be observed from a certain distance. If stopping is required, this distance is called the "stopping distance"; the more general wording is "the preview", signifying the required distance for the specific manoeuvre. The term "preview" is often used for the corresponding time interval as well; so, the preview is sometimes expressed in metres, sometimes in seconds (Godthelp, 1984).

The preview required in normal traffic has been investigated but not in detail. Schreuder (1985b) has presented several aspects of this. The conclusion was that for the stopping manoeuvre in Task I the rule of thumb giving several seconds has to be used and for Task II (where emergency stops may be more acceptable) a shorter time. For the other task aspects in Task I greater, often far greater, values of the preview are needed. A more detailed discussion of the preview aspects of road markings is presented in Sec. 4.4.

3.4. Required information for sub-tasks

Now the data presented earlier can be combined in a table in which the preview can be indicated for the different sub-tasks (the different manoeuvres) as defined earlier. The preview is based on considerations regarding the decision time, the time to execute the manoeuvre and the

decision-making level involved. As a result of the rather incomplete state of knowledge this table will give rough values only. With this in mind, the table presents a semi-quantitative description of the distances involved (e.g. "several meters" or "many hundreds of meters"). A conversion into numerical values is abstained from as that would suggest a higher degree of accuracy than is justified. In view of the large variations between different individual drivers as a result of their age, driving skills, experience etc, this state of affairs seems to be the highest "accuracy" that can be pretended to exist at present.
As a consequence of the large differences in preview values, it does not seem to be useful to make a fine distinction in the driving speed. It seems to be enough to introduce two speed ranges called "high speeds" and "low speeds". Broadly speaking these two correspond with rural (particularly motorway) travel and urban travel and could be expressed in speed ranges of some 80-110 km/h and 40-60 km/h respectively. For special cases (high speed freeways without speed limits) or residential yards - the woonerf -, additional classes of speeds may be considered over 110 km/h and under 40 km/h respectively.

The result is given in Table III. In this table there have been made additional simplifications. The elementary manoeuvres are listed as "stopping" and "other"; so is the classification of other traffic which will be discussed in the next section. The table is derived from the detailed discussion in Schreuder (1985c).
In Table III the relevant objects are listed for different task aspects and for the manoeuvres that are related to those aspects. In this table the manoeuvres as given in Table I are summarized and brought together in a number of groups. As the spread between individual observations is considerable, the number of groups of manoeuvres may be fairly small. As indicated earlier, the driving speed is divided in only two clases for the same reason. The relevant objects (the visually critical objects) finally are listed in the last column of Table III. For large preview it is primarily the road itself and its characteristics that is relevant. For smaller preview values, road signs and road markings become predominant. For "other traffic" the "other" vehicles are primarily of importance, whereas for Task II aspects again road markings are important.

3.5. Relevant objects

In Sec. 2.1 it was indicated that Task I contains the task aspects related to the need to reach the destination of the trip, particularly the selection and maintenance of the route. However, another important matter must be reckoned with: a driver is usually not on his own. Roads are used simultaneously by many road users, and the meeting of other users (other vehicles) is a very frequent affair. The situation becomes more complicated as here more than one driver is involved. They must not only see each other in time, but also they need to form an opinion about the behaviour of the other in the near future, taking into account the fact that the future behaviour will be influenced by the fact that the other driver is close and that they see each other. As a result of this complex situation accidents are often "caused" by misunderstandings between traffic participants. Nevertheless, it can be assumed that many situations and the consequent behaviour of the traffic participant can at least to a certain extent be predicted. If the prediction fails, however, accidents are likely to occur. Predictions of future behaviour are based to a large extent on what is customary to expect from other users under these or similar situations. Training, experience and recognition of the situation play an important role. In this respect, markings can contribute to a more easy recognition of the situations.

In Task I one has to discern two classes of relevant objects - objects that need to be observed: a) elements of the road (of which road markings and signs play a determining role) that are related to the selection and maintenance of the route, and b) other traffic participants. It is useful to subdivide these traffic participants in two groups: cars and other traffic participants. The reason is twofold: cars are large and therefore represent objects that can be observed already from a large distance, whereas other participants (pedestrian, pedal and motor bicycles, mopeds etc) are of small dimensions and are therefore not very well visible. The second reason is that these "other" participants are highly vulnerable; in collisions they will be injuried easily. The fact that motor bicycles belong to "fast" traffic and the other do not, is primarily a legal matter and is of limited importance when discussing the visual aspects of such objects, because the vulnerability is most important.

The relevant objects related to Task II cannot be indicated that easily. In fact, they include all obstacles that present danger, all obstacles (either moving or stationary) with which one might collide. As the avoiding manoeuvres are simple and small in number, the manoeuvre is selected as a criterion for the distinction of the objects. Here there seem to be three important classes: stopping, making large evading manoeuvres (swerving out etc) and making small adjustments (braking and/or steering).
These different relevant objects are included in Table III.

Relevant objects can be classified as "cues" and as "signals". In CIE (1985) a description of these concepts is given. The following paragraphs are based on that description.

The object itself or some characteristics of it (in this case described as "signal") is set up on purpose in order to convey a specific message to the observer. The message usually is directly connected to the driving task and usually require a specific response, such as: stop, or keep right. According to this description "road signs" should be classified as "signals".

Another type of information is conveyed by objects within the field of view that are self-explanatory. Such object are called "cues".
The information they convey is implicit and non-conventional. As an example, the curvature and lay-out of a bend will indicate to the (experienced) driver what would be the appropriate speed to round that bend. The distinction between signals and cues is not an absolute one. One may define an intermediate form: "markings". Markings may be considered as signals with a very simple message (such as "presence" and nothing more) or as cues that are placed on purpose without, however, the explicit purpose of conveying a coded message. A row of dots or cat's eyes on the road may have no particular coded message in the legal sense, but it marks clearly the centre of the carriageway.

The cue-objects, being mostly self-explanatory, offer at day under normal weather conditions little problems as regards their visibility, as long as they are properly placed, large enough, and show a distinct contrast (both as regards colour and luminance) with their direct background.

At night, or under situations of reduced visibility (fog, snow, heavy rain) most non-luminous objects are not visible any more. Some countermeasures are needed in order to maintain the information transfer. At night this is generally realised by shining light directly to these objects, trusting that they still will be self-explanatory. In other words, the major difference between day and night is that in daylight there are many cues for driver visual guidance. Therefore, individual cues need not be very strong. At night, most of the natural cues - road edges, embankments, shrubs, guardrails, etc. - are well below visual threshold and disappear. Therefore, drivers must be able to rely more heavily on the pavement marking system for path guidance cues.
This is only a brief summary of a very large field of experience. Further details are given in the CIE symposium on "Visual aspects of road markings" held in Paris on 2-4 May 1983 (CIE, 1983), see also Sec. 4.3.
A more complete treatment is available in the literature; see e.g. Adams (1976); Bryden (1981) James & Hayward (1960); Kenton (1978); OECD (1972, 1975, 1980); O'Flaherty (1972); Reid et al. (1962); Schreuder (1981a); SCW (1982); Serres (1975, 1981); Tooke & Hurst (1975); Triggs & Wisdom (1979).

3.6. Conclusions

- In road traffic, decision are made on line and in situ; they are based on the information that is collected in real time from the environment.
- The decisions are made on the basis of this information and on the information derived from the memory.
- The information from the environment is primarily of visual nature.
- The visibility of objects is subdivided as follows:

- detection: the object is <u>just</u> visible, it is at the threshold of visibility;
- conspicuity: the object is visible when taking into account disturbances and distractions from the environment and other task aspects (e.g. driving);
- recognition: the object is compared with memory contents, taking into account the likeliness of occurrence of the object under the prevailing situations.

- The distance from which the object must be observed when stopping is required, is the stopping distance. This stopping distance depends upon the (overall) reaction time of the driver and upon the vehicle (the brakes), the retardation and the driving speed.
- The required stopping distance under practical, realistic situations is considerably larger than the minimum stopping distance as well as the distances that are traditionally used in traffic engineering.
- The distance from which objects must be observed when other manoeuvres are required is termed the preview. The preview can be expressed in terms of distance (m) or in terms of time interval (s).
- The preview for all objects that are relevant for all manoeuvres and all traffic situations and task aspect can be listed and expressed in distances.

4. THE THEORY OF VISUAL GUIDANCE

4.1. Definition of visual guidance

In the practice of road lighting it has been tradition for a very long time to distinguish between three criteria of quality viz.: the light level (level of illuminance or luminance), the degree of (non)uniformity of the lights pattern and glare (De Boer, 1951; De Boer (ed.), 1967; Waldram, 1938, 1952). With increasing traffic speed and volume and with increasing refinement in the design and manufacture of lighting equipment, it was gradually felt that that the concept of guidance should be included (De Boer (ed.), 1967; Schreuder, 1967; Zijl, 1959). This concept is widely in use in landscaping of roads and in the overall design of road alignment. The concept is discussed in great detail in Lorenz (1971); see also Overdijkink (1959); Springer & Huizinga (1975). There were no ways, however, to quantify guidance, so that factual design was restricted to the earlier three. When the functional approach was introduced, it seemed that the guidance really is of a different category as the other three: it actually is a functional requirement (see Schreuder, 1974, 1977); see also Allen et al., (1977) and Forsberg (1978). And finally, when the approach based on the analysis of the driving task began to develop, it became clear that guidance probably is the most important criterion, particularly for roads that carry heavy traffic (Riemersma, 1983; Schreuder, 1984). To investigate this idea further, a series of experiments is being prepared; a first "pilot"-experiment proved to be very promising (Padmos & Walraven, 1982; Walraven, 1980; Padmos, 1984). It should be made clear here that guidance involves more than only the road lighting: guidance is an essential part of the transfer of the information to be processed by the driver. Road lighting is only one of the means to secure that the information is in fact available. Road markings have a similar role. In this respect road lighting and road markings are alternative means for the information transfer. The two supplement each other.

In the past visual guidance was not operational and not quantifiable. Furthermore, the theoretical framework for visual guidance is still inadequate. Research is urgently needed. It could be based on the consideration that guidance may be related to the comparison of the present to the recent past; in this way it might be linked to the research on short-term memory. In this respect the extensive experimentation made in the Netherlands as a joint effort of the Institute for Perception IZF-TNO in Soesterberg and the Institute for Road Safety Research SWOV in Leidschendam contributed very much to further knowledge and further possibilities for practical application. Similar research is planned in other countries (USA, UK and France).

The basic experiments are made by Riemersma. The aim was to find out which parameters in the outside world determine the lateral position on the road - in the traffic lane. It could be shown that course holding is determined by the time derivative of the heading angle and not by the heading angle itself nor by the lateral distance. Thus course holding is essentially a dynamic process that is governed by speed perception and not by magnitude perception (Riemersma, 1985). These findings were supported by the studies from other researchers as summarized by Riemersma (1979, 1979a). The consequence is that for course maintenance - the way one succeeds to keep an adequate lateral position in the traffic lane - the relevant information is gathered not from very short distance by peripheral vision (as is sometimes suggested) but from intermediate distances by means of foveal or parafoveal vision. This is in agreement with the studies from Rockwell and his collaborators, studies that were made with other objectives (Mantazo & Rockwell, 1967). In this respect, the studies of Rockwell et al. (1970) and of Zwahlen (1979, 1980) should be mentioned, where similar results were found while applying the method of measuring eye-movements.

4.2. Visual guidance for different manoeuvres

The experiments by Riemersma (Sec. 4.1) were made on straight roads. It was found that for straight roads and for different driving speeds the minimum required preview was about 5 seconds. This value is in good agreement with other values on which our earlier estimations were based (Sec. 3.3). In fact, the values are fairly large, suggesting once again that the traditional values of the reaction time are not very well based and probably not very relevant for road traffic.

For curves it is much harder to give figures. This is not a result from a more difficult experimental situation, since Riemersma (1984) indicated that from a theoretical point of view, curves can be investigated successfully with a similar experimental set up - an idea supported by other studies. In fact experiments of this kind were made in the past for finding a solution for a specific optical guidance problem (Blaauw & Riemersma, 1975). The problem is more of a practical nature. Curves come in different forms; the superelevation which depends on design speed and curvature restrict vision and so do guard-rails and other road furniture in the shoulder.
Based on similar theoretical considerations, a number of more practically oriented experiments were made. The overall result was that the difficulty in negotiating curves is more in the restrictions to recognise the radius of curvature and the arc lenght of the curve; the main problems present themselves before one enters into the curve. When, however, the driver is in the curve, it seems that as regards the maintenance of lateral position the situation is similar to that of a straight road.

Concluding it may be stated that, in spite of the fact that negotiating curves requires in different vehicle handling when compared to driving on a straight road, there does not seem to be a need to consider the required preview values differently in these two cases. This is stated for the required preview values in general, and it seems to be reasonable to state the same for the preview of road markings. Obviously, the shape and geometric requirements are different for the two conditions. So, when the vehicle handling in curves does not present additional problems - as one might expect for experienced drivers and adequate infrastructure - there seem to be no reasons to suggest different preview values for the visibility of road markings in curves as compared to straight roads. When, however, the drivers are not experienced, one has to reckon with the possibility of additional difficulties in the actual vehicle handling, particularly if driving speed and design speed (and superelevation) are not in agreement. No research in this field is known, so it cannot be indicated how far this represents an additional safety hazard that might call for different preview values for road markings, but one might assume that particularly in those situations, markings may be of special advantage. Obviously, here is a considerable gap in knowledge!

In Sec. 4.3. it is indicated that for long-range visual guidance road markings have only limited contribution. Here the guidance must be secured by other means. And finally, as regards visual guidance, intersections are similar to normal roads: apart from all sorts of considerations regarding other traffic, priority rules, signs and signals, drivers have to cross intersections or they have to make turns; in so far intersections do not differ from straight roads and curves repectively. Similar considerations hold for route selection manoeuvres and for emergency situations as indicated in Sec. 2.3.

4.3. Road markings as information carriers

In the foregoing sections, a general outline is given of the requirements for visual observation in traffic. In this section the road markings will discussed, more in particular the horizontal road markings. The section deals with the more general aspects of these markings as information carriers; in the next section (Sec. 4.4) the specific requirements as regards the preview in relation to these road markings will be discussed. First a few words on the terminology. The terminology regarding the marking of roads is somewhat complicated and not always consequent. In part this follows from the difficulty in translating from one language to another. In this report the following terms are used, similar to those used by CIE (1985) and OECD (1975).

* (Horizontal) road markings: the markings attached directly on the road surface. They include stripes of different materials (paint, thermoplastics, preformed sheetings, etc), different shapes (lines, arrows), different construction (reflectorized or not, profiled etc). Raised pavement markers are often included in the class of horizontal markings.
* Raised pavement markers (road studs, "cat's eyes" etc) are small individual elements that are attached to the road surface. They have the same or at least very simular functions as the (horizontal) road markings and are usually included in that class.
* Delineators are vertical elements that are placed in the shoulder at the side of the road. They are usually equiped with retro-reflecting divices. Their shape, location, colour and legal significance may differ widely between countries. These delineators (often called post-delinators) are not the subject matter of this report. A survey is given by Bernhard (1984).

As further explained in OECD (1975), a general awareness that uniformity of use of marking devices was desirable, especially because their geometric form and colour constitute messages to drivers, gradually led to a set of regulations specifying shape and colour of marking devices. International standardisation also proceeded and has led to the "Convention of Road Signs and Signals, opened for signature in Vienna on 8th November 1968" (Vienna Convention). In Europe, more detailed regulations are given in the "Protocol on Road Markings, Additional to the European Agreement Supplementing the Convention on Road Signs and Signals opened for signature in Geneva on 1st March, 1973" (European Road Marking System) of the E.C.E. (Economic Commission for Europe).
The regulations of different countries should be consistent with these international standards. However, the regulations of the United States "Manual on Uniform Traffic Control Devices for Streets and Highways" differ to some extent from those of the "European Road Marking System", although both are consistent with the Vienna Convention.

And finally, the OECD report stresses what was indicated earlier in this report: road markings have a number of functions, which lie in different levels of decision making. The major functions are related to:
- selection of the route (warning signs, locations, etc., indicated by letters and words);
- selection of specific manoeuvres (stop signs, directional arrows, stop lines, zebra crossings, etc.);
- control of specific manoeuvres like rounding bends, negotiating intersections, etc. (side markings, delineators, etc.);
- selection and control of elementary manoeuvres at the vehicle handling level; this pertains primarily to the control of lateral position within the traffic lane (lane markers).

4.4. The requirements for road-marking preview

Road markings have different functions in traffic. As can be seen from Table III the road and its characteristics and particularly the road markings form relevant objects for many manoeuvres, especially for the manoeuvres regarding route maintenance. Decisions related to other traffic participants (vehicles) require other sources of visual information:

signalling and marking of these vehicles. Vehicle markings are discussed in detail elsewhere (Roszbach, 1972, 1974; Rumar, 1970; Schreuder, 1976a; TRB, 1984).

The distance from which relevant objects must be visible, depends on the manoeuvre to be performed. For maintaining course and for maintaining the lateral position on the road the distances range according to Table III from "several hundreds" to "about ten" meters.
For the selection of the route - where road markings and directional signs supplement each other - and for the indication of special manoeuvres the preview must be such that the manoeuvre can be preformed in a reasonable way, without endangering traffic. Here general rules cannot be given but usually the requirements are not severe because most signals and signs are repeated several times. In these cases the long-range prewarning usually is ensured by the signs, and the medium-range observation is supported and sometimes taken over by the road markings. The decisions usually are of a cognitive nature, so that letters and symbols are used on the signs. The observation of symbols depends mainly on the knowledge of them. Rules are given in national Codes and Standards, and they mostly refer to special, well defined cases. It should be pointed out that the subject of visibility (readability) of signs is very well studied; see e.g. CIE (1986).

Finally, the objects for Task II. As said before, Task II is related to sudden, unexpected situations that require evasive action. Many of such situations are related to other traffic. Road markings have no function here. However, also in the road lay-out and alignment sudden unexpected situations may occur; they are fundamentally errors in the road design. Here, road markings may have an important function. As such discontinuities cannot be always avoided, particularly on existing roads, road markings may be used to improve the situation. It would be wrong policy, however, to accept the errors in the road design on the ground that the dangers of them can be avoided by applying or adapting road markings. As regards the preview, again here the distance (the time) need not to be large as in important cases of in dangerous situations the signs and signals are repeated. Usually, the markings are used to indicate the details of the road lay-out, whereas the warning for a dangerous situation is done by signs of signals or even by (flashing) signal lights.

In conclusion, one may state that the required preview for road markings is usually under 100 meters. This does not imply that road markings do not have a function at larger distances; in fact, they may contribute considerably at medium or long range (visual) guidance.

The considerations given here pertain to the requirements for road markings. It is essential, however, to know whether these requirements can be fulfilled. In Sec. 5.1 the supply-and-demand approach will be discussed in detail; here a few geometric considerations will be given related to the possibilities to observe road markings, taking the perspective view into account. These considerations are made by Blaauw & Padmos (1979, 1981) and adapted from CIE (1985).

These considerations are based on Blackwell's classical studies. Blackwell (1946) reported relations between size of a circular object, ambient luminance and threshold contrast, at which the object just starts to become visible. These relations were used by Allen et al. (1977) to determine the visibility distance. In order to apply these relations, the so-called "equivalent diameter" has been introduced. This is assessed as follows.

A road-marking stripe will be seen very much shorter in perspective due to the grazing viewing angle of the driver. The visual shape of such a marking stripe can be described by the vertical and horizontal viewing angles S_V and S_H.

$$S_V = 3438 \frac{h \cdot 1}{d2} \text{ (minutes)}$$

$$S_H = 3438 \frac{w}{d} \text{ (minutes)}$$

h height of driver's eye
l length of road-marking stripe
w width of road-marking stripe
d distance driver to center of road-marking stripe

The rectangular area (described by S_V x S_H) seen by the driver, can be substituted by a circle of the same area.

This circle has the "equivalent diameter" d_{eq}.:

$$d_{eq}. = 2 \sqrt{\frac{S_V \cdot S_H}{\pi}} \qquad d_{eq}. = 6876 \sqrt{\frac{h \cdot l \cdot w}{\pi \cdot d3}} \text{ (minutes)}$$

The equivalent diameter may characterize the viewing angle under which the driver sees the road marking ahead. It depends considerably upon the viewing distance and the size of the road marking and the height of the driver's eyes above road.

For two road marking stripes of 4 inches x 9 feet (0.10 m x 2.74 m) and 4 inches x 15 feet (0.10 m x 4.57 m) Allen calculates d and, based on Blackwell's data, the visibility distance. According to the data given in CIE (1985), when a road luminance of 17 cd/m^2 is assumed (which means illumination by fog or at sunset and cloudy sky, in other words relatively poor viewing conditions) - the visibility distance is approx. 50 m for a contrast of 0.04. Contrasts usually are, however, in the range of 0.1 to 3 which results in a visibility distance of at least 75 m.

Meseberg (1985) determined the range of luminance factors of road markings and road surfaces for the German motorway-network, and calculated the minimum contrast for different types of road surfaces, road markings and road-surface conditions (new and in-use, dry and wet surfaces). The minimum contrast was 0.25 which corresponds to a visibility distance of more than 75 m.

4.5. Alternatives to road markings

For short and medium distances of less than 100 m road markings are quite successful so there is little need to consider alternatives. It may be indicated here that there are many different types of horizontal road markings, all with different advantages and disadvantages and often different areas of application. Examples will be given when discussing the wet night visibility problem, one of the major problems in the area of road markings! (see Sec. 7.2).

In Sec. 4.4. we stated that road markings usually do not require a preview of more than 100 m. In case the preview should be in excess of 100 m, the effectiveness of road markings decreases considerably, resulting from the fact that they are observed from a low attitude: the eye-height of driver's eyes is about 1.10 m, and this height has a tendency to be even further reduced as the design of (passenger) cars, as reasons of taste and of fuel economy, call for lower car bodies. In the perspective image, horizontal objects on the road surface at distances of more than 100 m are not easily visible when viewed from 1.10 m high. Drivers of vans and trucks are in a more favourable situation, but that is of little importance as road marking are applied for all traffic participants. It should be pointed out that this restriction in being useful is a matter of geometry and not of headlight performance; see also Sec. 4.4. For larger?p distances alternatives are required to supplement and sometimes to replace the information presented by road markings. Usually delineators are used; also the overall landscaping of the road is important. Here a warning might be in place: traditionally, road landscaping is exclusively done on the basis of aesthetic considerations. There are many cases where such considerations are not in line to, or even conflicting with, considerations of road safety; see e.g. Lorenz (1971); Springer & Huizinga (1975); see also Sec. 4.1.

In some cases the visual information as required by the driver is supported by auditory or kinestetic cues. In this respect, rumble strips are applied to a considerable degree with a moderate degree of success as an accident countermeasure (Anon, 1984; Cahoon & Cruz, 1970; Capelli, 1973; Farrimond, 1968; Saville, 1969; Schreuder, 1980; Sumner & Shippey, 1975 and Visser, 1977).

It may be noted that profiled road markings ("ribbelreflex") that perform very well in wet conditions, orginally a were designed as rumble strips. Recently the auditory effects are considered as annoying rather than as helpful. Profiled markings are therefore only used away from areas where people live (Schreuder, 1985; Anon, 1980d, 1985, 1985a).

In this connection, the self-luminous road markings may be mentioned. The application at present is restricted to specific locations; in fact, usually they are experimental in nature. Examples are given in Creech (1976); Harrigan (1977); Hopkins & Marshall (1974); Schwab (1972); see also Schreuder (1981a). A recent development applies fiber-optics to avoid electric wiring in the road (Anon, 1986a).

4.6. Conclusions

• Road surface luminance, the degree of (non)uniformity of the luminance pattern, the glare and the (visual or optical) guidance are the four criteria for quality for road lighting installations.

• Guidance is a functional requirement.

• Guidance is provided by the overall road lay-out, the landscaping, the run of the road, the lighting installation (if present) and the road markings.

• Recent research suggests that guidance is often the most important of the four quality criteria.

• Different manoeuvres require different guidance. This implies different values of the preview for the provisions made to improve guidance.

• Under normal conditions, the required preview for straight roads and for curves are of comparable magnitude.

• Further research is required to establish how far road markings may support the guidance, particular under non-normal conditions, in curves and for unexperienced drivers.

• The required preview of road markings usually is under 100 meters. A larger visibility distance may enhance the visual guidance.

These conclusions will be the basis for the development of functional requirements on road markings as will be discussed lateron.

The foregoing chapters dealt with the requirements to be fulfilled by road markings in order to be effective as means to support the visual observation that in its turn is required for a safe traffic. As will be indicated in the next chapter all this is part of the "demand"-side as opposed to the "supply"-side.

5. PHOTOMETRIC AND GEOMETRIC FACTORS

5.1. Supply and demand

The foregoing chapters dealt with the requirements for road markings. As these requirements are related to the function of road markings in traffic as a tool for accident prevention, the requirements are called "functional requirements". They indicate what the system must be able to do in order to function properly. These functional requirements represent the "demand": the things one demands from the system so that its function is fulfilled. It is a matter for further consideration for Chapter 5 to find out in which way the markings supply more than these demands, that is if the supply exceeds the demands - or at least equals them. In this way the well-known "supply-and-demand"-model can be applied to road markings. It was introduced in the considerations on road lighting by Blackwell (1959; see CIE, 1972) and worked out by Schreuder (1970, 1970a, 1977). There is still some confusion about these issues as may be seen from the fruitless discussion between Economopoulos (1977) and Gallagher et al. (1972, 1974, 1977). The one dealt with the supply side, the other with the demand side. As soon as this was realised, not only did the difference of opinion disappear, but also could it be shown that both experiments supplement each other quite nicely (Schreuder, 1982, 1983b). In order to compare supply and demand, it is necessary to express them both in the same quantity. Blackwell (1959) tried to use visibility (detection). This did not result in a satisfactory result, so all sorts of emperical field factors needed to be included. This may be an acceptable procedure in practical solutions, its does, however, not help in solving more fundamental problems. In tunnel lighting the same was found by Adrian (1976). As indicated already in Sec. 3.1 a considerable improvement was found in using the concept of conspicuity instead of visibility, as introduced by Schreuder (1970a). Usually the conspicuity is taken into account by applying a multiplicative factor to the threshold values in order to arrive at numerical values for the conspicuity. As said, this can be done only in practical situations (as done by Schreuder & Oud, 1985 for tunnel lighting). Furthermore, the emphasis on conspicuity had severe drawbacks, and it is questionable whether it really it always beneficial to the road safety. So, as indicated in

Sec. 3.1, one should prefer the recognition. Here, one meets again the difficulty that recognition does depend on the observer and therefore cannot in isolation be quantified for the objects to be observed.

At the present state of knowledge, particularly as regards the driving task, there seems to be no easy solution. So - in agreement with what is done usually - the conspicuity will be used as a criterion for comparing the supply and the demand, with the proviso, however, that when assessing and evaluating the results of such comparisons, the aspects of recognition will be taken into account - if not in a quantitative way then at least in a qualitative way. In this way, severe errors as have been made in the past, probably can be avoided. It will be clear, however, that this is not a satisfactory state of affairs; further fundamental research and practical development into the area of visual observation in traffic are urgently needed.

5.2. Vehicle headlamps

The lighting equipment provides the supply of information. For night-time traffic, two types of lighting may be distinguished: public (overhead) lighting and vehicle headlamp lighting.

Public lighting is, like daylight, primarily a diffuse type of lighting: light comes from many different directions. Under such circumstances, the visibility of objects is primarily determined by the luminance contrast that exists between the objects and their immediate background - e.g. a road-marking stripe and the road surface on which it is attached. The contrast is determined in the first instance by the difference in the luminance between the different objects, and that in its turn depends upon the difference in diffuse reflection of the materials. It should be noted, however, that for the glancing angles of observation that are common in motorised traffic, this is an oversimplification: the amount of light reflected by the surface depends upon the directions of light incidence and of observation, and should therefore be described by a tensor. The details of public lighting engineering and of the influence of the reflection characteristics of the road surface are discussed in detail in De Boer (ed.) (1967), Van Bommel & De Boer (1980) and SCW (1984).

When considering the visibility of road markings and the possibilities to enhance the visibility particularly under adverse conditions, vehicle headlamp lighting is more important, because it usually is much more critical. A great deal has been published on the merits of vehicle headlamp lighting, and the different solution to counteract specific problems. A survey is given by Schreuder (1976, 1976a), see also SWOV (1969).

Vehicle headlamps are attached to the vehicles in order to light the way ahead. This means that the direction of illumination and the direction of observation are virtually co-incident. Under these conditions, it is not the overall or diffuse reflection that counts; it is the retro-reflection, i.e. the degree to which light is reflected into the direction where it came from. Many surfaces show a considerable degree of retro-reflection; however, this degree of retro-reflection can be enhanced in a very marked degree by applying specific constructions. Objects made along such contruction an called retro-reflecting devices, or retro-reflectors. On roads without public lighting, the only light available at night is provided by vehicle headlamps (Obviously, pedestrians and pedal bicyclists are severely at a disadvantage!). It is customary to apply retro-reflecting devices at the different objects that are important on these roads to maintain course - more in particular on the road markings. Details will be given lateron (Sec. 5.3), but first some information will be given on the vehicle headlamps.

Vehicle lighting consists basically of two beams: high beams (driving beams) and low beams (passing beams). Usually the two beams, that can be used alternatively, are provided by the same optical unit containing one lamp with two filaments. Often, for the high-beam mode, special lamps are added. The high beam may have a high intensity in this way - 400,000 cd or even considerably more straight ahead (Schreuder, 1976a). The reach of such beams is considerable; particularly retro-reflectors can be seen at many hundreds of metres.
As a result of the glare that opposing drivers will experience, high-beams cannot be used in passing situations. Here, the passing (a meeting) beams are required. These beams are characterized by a sharp "cut-off": very little light is counted above the horizon, so that glare for opposing traffic is reduced, whereas the intensity under the horizon is

considerable - be it much less than with high beams. The cut-off results in the fact that, straight ahead, very little light will reach the road at a distance more than some 60 m ahead of the car. A further draw-back of this sharp cut-off is that mis-aim, even a minute mis-aim, may cause excessive glare. And so does water or dust that may collect on the front lens of the head light.

Summing up, vehicle headlamp lighting, particularly on low beams is only a compromise between increasing the illumination and reducing the glare. This compromise is inferior even to mediocre public lighting, even when the modern developments in vehicle lighting are considered (Schreuder, 1986).
Nevertheless, in many cases public lighting is too expensive to consider, so vehicle lighting is still the predominant lighting mode for night-time traffic, and therefore it is justified to design road markings specially with vehicle headlamps lighting in mind. This means, of course, the application of retro-reflecting devices.

5.3. Retro-reflecting devices and materials

A special case presents itself when discussing roads without public (overhead) lighting. Here the only available light at night is coming from the vehicle headlamps, and on all roads that carry more than the lightest traffic, headlamps on low-beam mode. In passing we might mention the proposals to use polarised light which enables to have a high luminous intensity combined with low glare. Although this system promises to solve most of the night-time visibility problems in motor traffic, one must fear that introduction is still far away (see e.g. OECD, 1976; Hemion, 1969; Johansson & Rumar, 1968; Rumar, 1974; Schreuder, 1976a).

In order to enhance the visibility of objects that must be visible in low-beam headlamps it is essential to apply retro-reflecting materials, that help to increase considerably the luminance of these objects when viewed from a position close to the light source. This, of course, is relevant for vehicle lighting: the eyes of the observer are close to the headlamp. It may be added here that retro-reflecting materials prove to be very useful on roads and streets that have public lighting. In fact, it is customary in many countries to equip all road markings with retro-reflecting materials, independent of whether the road carries public lighting or not.

The matter of retro-reflecting materials and devices has been studied extensively; there is a large number of publications available. Only a few general surveys will be mentioned here: Dutruit (1974, 1980); see also Anon (1982); Anon (1986e, f); CIE (1982, 1983, 1984, 1985) and Schreuder (1980, 1985). CIE (1982) and OECD (1975, 1984a) concentrate more on matters of selection of materials and on measurements and testing. The theory of reflection is discussed in depth by Chandler (1954, 1954a), Vedam & Stoudt (1978) and Stoudt & Vedam (1978, 1979); see also Anon (1974) and Stephenson (1983). Simple explanations and instructive experiments regarding retro-reflectors are given in Jacobs (1982) and Walker (1986); see also Schwab (1985).

Retro-reflectors come in three distinct types. The first, the cornercube or prismatic devices, apply the principle that light always is reflected back in the direction it came from when it is reflected consecutively by three mirrors that are perpendicular to each other like the corner of a cube. Essentially this is mirror (specular) reflection, be it in a rather special configuration. The second uses the fact that a sphere has not one single axis of symmetry: any cross section is in fact an axis of symmetry. Here glass spheres are used to focus the incident light on a concentric mirror that reflects the light in such a way that it is emitted from the sphere as a parallel beam of light in the direction from where it came - again a true retro-reflecting device. Optically speaking it is a concentric system. The third system looks like the second: again here glass spheres are used to focus the light, but instead of a mirror it is focussed on a diffuse - usually white - surface. The sphere again transmits the light as a parallel beam in the direction from where it came. The fundamental difference between the second and the third system is in the fact that the reflection in the former essentially is a regular (mirror) reflection and in the latter a diffuse reflection. The practical consequences of this are considerable: the "true" retro-reflectors may yield a very high degree of retro-reflection, whereas the third type only has moderate values.

The first type is usually incorporated in devices that are applied as separate "reflectors" to all sorts of objects that must made visible: cars, delineators, bicycles, pedestrian clothing etc. The second is applied as reflectors with lenses of about 0.5 to 1 cm in similar applications, and as sheet material with spheres that are much smaller (0,1 mm or considerably less). They have a very wide field of application: number plates, traffic signs and route signs, clothes etc. The third type is nearly exclusively restricted to road markings.

In practice road markings are either stripe type or isolated element type. The first are nearly exclusively of the diffuse type discussed above as the third type; the isolated elements include mostly either the first type (prismatic reflectors) or the lens type (cat's eyes). Often the different types are used in combination; modern development show a number of "in between" (hybrid) solutions. As these usually are not yet commercially available on a large scale it is difficult to say much about it; the developments are, however, very important indeed.

5.4. Photometric and geometric requirements

In the earlier chapters the functional requirements for road markings were described. From this the demand as regards the photometric and geometric factors may be derived.
The photometric requirements can in principle be expressed in the luminance of the marking, but taking into account that the road markings are always attached to the road surface, the contrast seems to be a more sensible measure. The contrast means here the contrast in luminance between the marking and the road surface immediately joining the marking. It seems to be sufficient to consider exclusively the luminance contrast and to disregard the colour contrast as all road surfaces can be regarded as "grey" at least for practical purposes and as road-marking materials prove to be equally visible independent of their colour. This was found when considering whether the colour of road-markings could be used as a coding dimension in traffic - which it could not! (Schreuder, 1978); see also Schreuder (1972). This holds of course for more "normal" surfaces and markings; there obviously exist surfaces and markings with very pronounced colours where the colour contrasts should also be taken into

account. These surfaces and markings are, however, not in general use and restricted to very special cases.
Using the (luminance) contrast as a criterion is no problem for markings that are composed of stripes etc. They are so large that the visibility is gouverned primarily by the contrast and not by the size (Blaauw & Padmos, 1979). For raised pavement markers this might be different, particularly at night when the markers have reflectores of the lens type ("cat's eyes"). These reflectors are too small to be observed as surfaces; they present themselves as point sources, the observation of which depends primarily on their luminous intensity and not on their luminance (CIE, 1985, 1985a; Schreuder, 1985).

The requirements for the contrast of road markings is investigated in detail in the Netherlands by a joint Working Group of the Study Center for Traffic Engineering SVT and the Study Center for Road Construction SCW. The investigations made under the auspicies of this Working Group have been published in a number of places, see e.g. Blaauw & Padmos (1981, 1982); Blaauw et al. (1983); Van Gorkum (1982, 1983, 1984, 1984a) and SCW (1986). Research from other countries have been taken into account. Two studies of the relevant literature have been made, one at the outset of the study (Schreuder, 1981a) and one at the end (Schreuder, 1985). It was clear that in many countries similar considerations were followed.
The final report of the Working Group is nearly completed but the results of the experiments are published already and are used in the report presented here. The objective of that Working Group was primarily to investigate the wet night visibility under vehicle lighting and to give recommendations to the Ministry in the Netherlands regarding the road marking in unlit rural roads, particularly on rural motorways. In order to set up these recommendations other aspects were investigated as well, particularly the photometric requirements for the fulfillment of the functional requirements - the question considered in this section. In the SCW study, the results are presented in such a way that the minimal requirements as regards the reflection properties of marking materials can be assessed. They are not, however, directly indicated. (Because the report is not published, the assessment will be made on the basis of the SCW data as published in Blaauw & Padmos (1982); see also Van Gorkum

(1982)). The requirements for stripes are:
0.2 $cd.m^{-2}.lux^{-1}$ for 80 km/h
0.4 $cd.m^{-2}.lux^{-1}$ for 100 km/h.
For raised pavement markers, the requirements are:
0.004 $cd.lux^{-1}$ for 80 km/h
0.006 $cd.lux^{-1}$ for 100 km/h.
These data are found by combining the data of the Figures 3 and 8(a) from Blaauw & Padmos (1981) (Reproduced here as Figure 1 and 2). The earlier date regarding the required preview (Godthelp, 1984) have been taken into account.

It was found that the colour of the road marking could be observed but it did not influence the visibility.
As indicated, these values are valid for unlit roads at night. The visibility of road markings on roads with public lighting and during the day was not investigated in this study. By "extrapolation" of the values quoted earlier in this section, that were assessed for unlit (rural) roads, the following remarks can be made:
- On roads with (overhead) road lighting - even those with in a intermediate level of luminance - the state of adaptation of the visual system of the observers/car drivers is such that the threshold for the contrast sensitivity is quite low: even small contrasts can be observed. This holds even more for the day situation. Based on the studies used for road lighting one may expect that in a road lighting of medium or high quality (a luminance of more than say 0,5 cd/m^2) a contrast of 10% seems to be sufficient for adequate observation (De Boer, 1951; Adrian, 1980; CIE, 1972; Schreuder, 1964). For daylight a contrast of 5% is probably already enough. Obviously it is no practical problem to ensure these contrast values with normal road marking materials.
- On roads with low-level lighting (about 0,5 cd/m^2 or lower) vehicle headlamps begin to contribute to an appreciable degree; it seems justifiable to apply the results found for the unlit roads. In practice this means that road marking should be retro-reflective.
- Raised pavement markers are small and their intensity is high - as long as they are lighted by low-beam headlamps - so it seems that in roads with overhead lighting the same values as given for unlit roads can be applied.

- The daytime visibility of raised pavement markers is a problem. They are small so that their visibility is ensured only if the contrast between marker and road is fairly high. This is in practice difficult to ensure as the usual materials are rather dull, and as retro-reflecting materials by definition are not bright in diffuse illumination (CIE, 1984; Schreuder, 1985). It has been found in practical experience that for the reason of daytime visibility raised pavement markers on their own are not satisfactory ; they are usually combined with stripes. This is a practical point: it does not seem to be very helpful to describe in detail what should be the ideal contrast between the marker and the road surface to render them visible if this value cannot be realised in practice.

These points are constructed "by extrapolation" from the research results of the SVT/SCW-study. These findings are very well in agreement with other studies. These studies usually are visibility studies and not requirement studies, but the results can be compared particularly on a relative basis. Schreuder (1985) surveyed many of those studies. In particular, the almost "classic" study of the State of Georgia should be mentioned, where different road-marking materials were compared in practical visibility studies, in laboratory tests and by means of calculations. It was found that in wet night-time conditions without (overhead) road lighting the visibility (here conspicuity) of the markings decreased in the following order:

- raised pavement markers, cornercube type ("Stimsonite");
- raised pavement markers, "cat's eyes" type;
- light aggregate as marking ("Luxovite");
- thermoplastics, beaded;
- traffic paint, beaded.

It was striking to note that in dry daylight conditions, the order of conspicuity was exactly reversed: the traffic paint was the most conspicuous, and the raised pavement markers were the poorest (Tooke & Hurst, 1975). Actually the visibility studies of the SVT/SCW-experiments did prove the same (SCW, 1986). It may be noted that all marking in the test were retro-reflecting with the exception of the light aggregate. This is an artificial material (calcinated flint) that is extensively used in Scandinavian countries as an aggregate for road-surface top layers and for surface treatments and overlays because of its high (total) reflection (SCW, 1984). Exceptionally they are used as well as road markings, particularly for edge markings.

The geometric requirements are less complicated. Here, the dimensions are sufficient to describe the markings. As road markings are seldom narrower than 0.10 m the size is always quite ample to secure visibility. The visibility is nearly exclusively determined by the contrast. Therefore, the dimensions do not influence the visibility. The question how long the stripes should be and what is the best interdistance is not a matter of visibility. It influences the way in which the markings can be recognized as an interrupted row of "bars" or as an uninterrupted longitudinal line. The standards of different countries show large differences; there are extremes where the observation is adversely influenced. The ratio stripe/interdistance varies from 1 : 1 to 1 : 13 for normal sections of road. Most common is 1 : 2 (see e.g. Schönborn & Domhan, 1981). For advance warning, a ratio 2 : 1 is sometimes used.

The geometrical aspects of raised pavement markers have been indicated already: the markers themselves are so small that they are not well visible in diffuse light, i.e. when their retro-reflectors are not effective. This implies that raised pavement markers cannot be applied on their own, but they should be used in combination with stripes. An exception to this is the way as they are some times used in temporary installations e.g. road works. Here the interdistance between the markers is such that visually they form a "line". The interdistance must be not much more than about 0.60 m.

Finally, a few words about the colour of road markings. The visibility of markings is determined primaraly by the (luminance) contrast between the marking and the adjoining part of the road surface. Road surfaces usually are dark grey, so that the maximum contrast can be arrived at by making the markings as light as possible. This implies white or yellow. In case of very light road surfaces (portland cement concrete or asphalt concrete with light additives) the contrast between the markings and the surface may be small; sometimes a dark rim is made around the stripes (Schreuder, 1973a; Meseberg, 1985; CIE, 1983). It should be noted that under the prevailing glancing observation angles, the colour of the surfaces (the road surface as well as the marking) is not easy to observe. The reason is that most of the light is reflected by the top boundary of the surface material; the reflection is determined more by the texture of the surfaces than by their actual colours (Schreuder, 1965). The result is that in practical situations the colour of the marking as well as the colour of the road surface cannot easily be observed from the position of a car driver, notwithstanding the fact that for steep viewing angles - as pertain for pedestrians - the surface may show marked colours.

In several countries the colour of the road markings are used for signalisation purposes. The foregoing will make clear that this is not a very effective way; this considerations played a role when the colour of yellow was discontinued in Europe to mark one-way roads (Schreuder, 1978).

5.5. Conclusions

- Functional requirements on road markings can be expressed in the supply and the demand of visibility: in order to function adequately, the supply should exceed or at least equal the demand.
- The supply and demand can be expressed in terms of visibility (detection) or conspicuity. More relevant for traffic situations, however, is the recognition, taking into account the contribution of the observer.
- For the observation of road markings, three illuminants are of importance: daylight, public (overhead) lighting, and vehicle headlamp lighting. The vehicle lighting usually is the most critical.
- In vehicle headlamp lighting, the directions of illumination and of observation coincide nearly completely. Under these conditions, the application of retro-reflecting devices is most effective.
- vehicle lighting has two modes: high beams for driving in the open, and low beams for use when opposing traffic is close-by. Low beams form a compromise between enhancing the illumination and restricting the glare. The reach straight ahead of low beams usually is less than some 60 m.
- Retro-reflecting devices consist of optical elements: either corner-cube reflectors or spherical lenses.
- In road markings, usually the light that is focussed by the spherical lenses is not reflected by a mirror as is the fact in many types of sheet

materials and in "cat's eyes", but it is reflected diffusely by the white matrix of the marking. The resulting retro-reflection usually is low in comparison to "true" retro-reflecting devices.

- Adequate visibility of road markings is ensured if they show a reflection of at least 0.4 $cd.m^{-2}.lux^{-1}$ (for 100 km/h).
- The colour of road marking materials is not important.

6. RECAPITULATION; CONCLUSIONS

In the foregoing chapters of this report we discussed in detail the requirements for road markings. In this chapter we will recapitulate this, and summarize the conclusions to be drawn from this. In the next chapter we will discuss the "supply" side: what can the system (the road marking system) offer the road user; in how far is it possible to fulfill the different requirements? Is it possible with products that are available today, or are new products new developments, new ideas necessary? And if so, how can we reach these new products, new developments and new ideas? The next chapter will only begin to outline these points, because a full treatment of this is the objective of the next phases of this project. But first the recapitulation.

Road markings are part of a system that is introduced to promote safety for the road-transportation system. Such a transportation system is understood to be a prerequisite of our present society where production and consumption are far apart so that a large amount of transport is needed - transport of goods, of persons and of information. This transportation system has benefits for society; it has also costs. Part of these costs are essential - the system could not work without them: construction and operation costs. These costs can never completely be avoided; they are essential for elements that cannot be missed. Another part of the costs is in this sense not essential at all: one could perfectly well think of a transportation system where these costs are absent: the costs of accidents, of social and environmental pressure etc. It is the objective of a road-safety policy to reduce these unwanted and unnecessary costs as far as possible; particularly the accident costs (both monetary and non-monetary costs). This objective is actively pursued, even if it is to be expected that the goal - a transportation system without accidents - probably never will be reached.

The extent of the unsafety can be found from accident studies. Such studies can also help to find statistical correlations between the accidents and specific parameters in the transport system. In order to find causal relations, however, analytical studies are required. Ideally, such analytical studies would require an accepted and acceptable model of road transport and road safety. Since such a complete model does not exist at present, the analysis is restricted to the driver behaviour (the behaviour of traffic participants as participants).

This approach concentrates on the analysis of the driving task (of car drivers). This task consists of two main task elements: Task I relates to reaching the destination of the trip, and Task II relates to avoiding accidents when underway. Both tasks are essentially information processing tasks and more in particular decision-making tasks. The decisions are made using the information gathered from the environment. In most cases this information is compared to information that is acquired from the memory. When a decision is reached, actions are performed that ultimately result in movement (or of changes in the movement pattern) of traffic participants or their vehicles.

The decision-making processes related to Task I can be placed in a hierarchical system. The higher levels of this system are related to the socio-economic aspects of the transport system and to the selection of mode of transport and of the route. These levels are not directly relevant for this study. Lower levels are, in contrary, most important. They deal with the selection of manoeuvres (complex manoeuvres and elementary manoeuvres) and with vehicle handling. Still lower levels deal with the vehicle operation and can be disregarded here. For each of these levels a number of manoeuvres can be indicated and for each of these manoeuvres it can be indicated what are the relevant objects that must be seen - how, at which distance etc. Other task aspects deal with the encounter of other traffic participants; they are not related to road markings and are therefore not discussed. Finally, Task II consists of avoiding danger as a result of sudden unexpected and unwanted incidents. The evasive manoeuvres usually are simple; road markings may offer additional support to perform these manoeuvres as effectively as possible.

In this way a list of objects can be constructed that must be visible in order to have adequate traffic (as regards both tasks). For each of these objects it is indicated at which distance they must be visible. In this list of objects, road markings have an important place.

The result is that they must be visible at distances over some tens of meters. Horizontal road markings are attached to the road surface itself and therefore cannot be seen easily at distances much more than above one hundred meters. This limits the primary area of application of road markings. For larger distances other means are needed to supplement the information provided by the road markings. Such means are available, but they fall outside the scope of this report.

The functional requirements for road markings are therefore restricted to the following: they must be visible at distances between some 20 or 30 m, and at least 100 m. They function both for maintaining the course (Task I) and for avoiding emergencies (Task II).

As the situations under vehicle headlamp lighting usually are the most critical, these conditions do receive the most emphasis. As in vehicle lighting the directions of illumination and observation nearly coincide, it is for these conditions that retro-reflecting devices are required. In fact, nearly all road markings are equiped with retro-reflectors.

The functional requirements lead to photometric and geometric requirements: the requirements that must be fulfilled so that the functional requirements can be met. For road markings of the "stripe" or "bar" type the visibility is determined by the (luminance) contrast between marking and road surface. On roads without (overhead) road lighting, that are lit exclusively by vehicle headlamps, the stripes need to show a reflection of at least 0.4 $cd.m^{-2}.lux^{-1}$ (for 100 km/h). The same holds for roads with low quality lighting. For high-level lighting installations and for daytime the contrast needs not to be more that than about 10% and 5% respectively. Raised pavement markers are much smaller; their visibility is determined primarily by their luminous intensity. Therefore they are usually equiped with retro-reflecting devices. These devices need to show a reflection of at least 0.006 $cd.lux^{-1}$ (for 100 km/h). This holds for all nighttime situations both on lit and on unlit roads. In most cases adequate daytime visibility cannot be ensured, so that raised pavement markers are usually used in combination with stripes.

The geometric requirements are related to the photometric requirements. Road markings that are wide enough, so that the visibility is determined by their contrast, are well above the minimum size to be observed; the size does not need, therefore, to be considered any further. The length of the stripes and their interdistance are not important for the visibility, although they may be important for the recognition. Raised pavement markers are too small to be observed easily when isolated. Therefore they are preferably applied in combination with stripes. When, however, their interdistance is less than 0.60 m, they may be observed as continuous lines.

7. THE SUPPLY SIDE FOR ROAD MARKINGS

7.1. Introduction

This chapter deals with the supply side of road markings: the degree in which the markings succeed in offering the necessary information the driver requires - the degree in which the demand is met or surpassed. In principle one could follow two distinct courses. The first, the theoretical, is to start from the functional requirements and the ensuing photometric and geometric requirements and proceed to design a road marking material that is able to fulfill these requirements under all possible conditions. The second, the practical - or the pragmatic - is to take into account the fact that road markings are manufactured and applied for many decades; that they are reasonably successful under some and that they fail under other conditions. On this basis one could proceed to improve the existing materials in such a way that gradually they perform better under more conditions. This approach implies that the functional requirements are specified for many different situations and that it can be studied in how far these specified functional requirements can be met either by existing road marking materials or by adapted or even new products.

This research project concentrates on the second course; it is primarily a pragmatic project aimed at improving products and materials, and applying them better. The first course, the fundamental one that may lead to completely new concepts in road marking, and to new materials, products and applications methods will, however, be taken into account in the third phase of the project. The second phase will concentrate on development and improvement.

The first phase of the project, that serves to a certain extent as a "pilot-experiment", aims primarily at presenting the theoretical framework on which the second and more in particular the third phase will be based. This framework has been developed in the earlier chapters of this report. The present chapter is to be considered more as an example in which way the functional requirements can be specified and in which way the road marking materials and products can be adapted or improved in order to meet these specified functional requirements. For the example the wet night visibility will be selected.

7.2. The wet night visibility of road markings

7.2.1. Traffic and safety aspects of wet roads

In the preceeding chapters, the visibility of road markings is discussed in general terms. It was indicated that the visibility may be affected adversely by certain conditions related to the observer or to the environment. Now a very specific example of this will be discussed: the degree to which the visibility of road markings is affected by rain and other water on the road (puddles, dew etc.), more in particular at night on roads without public (overhead) lighting. Unlit roads are selected for this discussion because here vehicle headlamps are the only illuminant. It should be noted, however, that wet markings usually are hardly visible at all under public lighting as well.

The condition discussed in this section is a specific one. First, as daylight and public (overhead) lighting are absent the only source of light available is the vehicle lighting. As has been shown elsewhere, for most practical conditions particularly on densely trafficked roads, this means low-beam headlamps (CIE, 1974; SWOV, 1969; Schreuder, 1976, 1976a; Fisher, 1970, 1970a; Fisher & Hall, 1970; Attwood, 1976; Rumar, 1970 and De Boer, 1955). In terms of guidance this means that the preview cannot be more than the reach of these low beams; with traditional lamps this amounts to some 60 m straight ahead and slightly more along the near-side kerb (the right side in countries with right hand traffic) (De Boer & Morass, 1956; De Boer, 1955; Schreuder, 1979). With modern halogene lamps it may be somewhat more, but not very much as also these lamps are supposed to fulfill the requirements as regards glare restriction (De Boer & Schreuder, 1969). So in view of the preceeding discussions, both road markings and lighting equipment have similar restrictions as regards the preview: usually less than about one hunderd meter. For the decisions regarding manoeuvres that require a considerably larger preview, other sources of information are needed. Ordinarily this information is provided by the marker lights and the signals of preceeding vehicles: on a heavily trafficked road there are always preceeding vehicles! This holds for the maintenance of the course and also for the performance of manoeuvres related to stopping or speed changes; the first by means of the marker lights (tail lights) and the second by means of the signals (stop lights). A completely different situation presents itself when due to restrictions in the (meteorological) visibility the lights of preceeding vehicles are not visible. This condition is to be found in fog, heavy rain or snowfall. Here, road markings may have an important function in supporting drivers in maintaining course and (lateral) position. It should be added that retro-reflecting devices are less effective in fog, as the light has to travel twice the distance (Spencer, 1960; Schwab, 1972; Oppe, 1985; Schreuder, 1964b).

Rain is a very unfavourable condition for the road traffic. Two main sources of additional danger are: first, the skidding resistance of road surfaces is reduced considerably when wet. In fact, the skidding resistance in dry conditions is never measured, as all dry road surfaces prove to be adequate in this respect. All wet roads perform considerably less; however, there are very large discrepancies between different types of road construction. Furthermore, the driving speed is important. The skidding resistance decreases with increasing speed - unfortunately so, because at high speeds the requirements are higher. The reason is that during and shortly after rain a more or less continuous sheet of water forms itself on the road surface; this layer prevents, by forming a wedge, that a moving wheel can touch the surface itself. In extreme cases, the wheel (and the vehicle) "floats" on top of the water layer, and the braking facility is reduced to nearly zero. At lower speeds the water wedge is less strong so that the wheel may touch the surface to a certain extent. The solution is simple: one must ensure that the wheel (the rubber of the tyres) may reach and touch the surface (the stones of the road aggregate). Still, because both are wet, the friction is less than that in dry condition, but is usually adequate - provided of course that the stones are not polished by the traffic. This can be ensured by providing profile on the tyre and on the road - preferably on both. In practice, it is found that whatever the tyre profile, the road must be profiled as well: it must show an a considerable "texture depth". The water must go somewhere; the road surface must have therefore a certain drainage capacity. This drainage capacity of the top surface may be enhanced by grooving, a practice often applied with Portland cement-concrete roads. The different aspects of skidding resistance and the influence of water on the road are discussed extensively in the literature. Surveys are given by Bonnet & Poilane (1985); OECD, (1984a); SWOV (1973); Paar (1975); Kamplade (1981); Hofmann (1979); Ross & Russam (1968); Anon (1981); SCW (1977, 1984); Sabey (1968); Schlösser (1975); Schlösser & Doornekamp (1979); Tromp (1985); Welleman (1977, 1979, 1980). The reason we have mentioned the problems in this report is that road markings are part of the road surface as well: they have to perform as well under wet conditions, and they must show an acceptable skidding resistance. In fact, national codes and international recommendations give numerical values for the skidding resistance for road markings both in wet and dry conditions. More in particular, the drainage aspects of road markings are of the highest importance, as will be indicated in the following sections.

Recent developments in road surface construction focus on drainage aspects. The first prerequisite is to have a large percentage of hollow room in the top layer, where the rainwater falling into the road may be stored. Modern surfaces often have a hollow-room percentage of over 15% as compared to 3 to 5% in traditional surfaces. Even more effective is to ensure that the hollow rooms are interconnected so that the water can drain under the actual top surface towards the sides of the road. This modern development is aptly called "drainage asphalt"; other terms are porous asphalt, porous friction course etc. In 1976, an international conference was held on this subject; the proceedings of that conference give an excellent survey of the state of the art at that moment in time (SCW, 1977a). Research is continuing; the more recent findings are summarized in SCW, 1977 (see also Van der Snoek, 1982). One point should be added regarding road markings on these surfaces. Practical experience did show that a somewhat larger amount of paint or thermoplast is needed than a traditional road surface; the difference, however, is not large. As a result of the great texture depth, the useful life of the markings is considerably larger than on traditional road surfaces, so that this compensates to a certain extent the higher use of road marking material.

Another factor of the water on the road surface during or after rain is the reduction in visibility. Rain itself also reduces the (meteorological) visibility; this effect usually can be disregarded, particularly in the rain conditions as are prevailing in Europe. Splash and spray (water thrown up by passing vehicles) can be much more severe; quantitative data are, however, scarce (Padmos, 1984). Also in this respect, drainage asphalt may offer a considerable advantage over traditional road surfaces. As regards the road surface itself, the water layer acts like a mirror and reflects most of the incident light away from the light source. For roads with overhead lighting installations the end effect can be an increase of the average road-surface luminance. Still the overall effect of a wet surface is even then mostly unfavourable as the degree of non-uniformity of the luminance pattern usually increases to an unacceptable level. All this is discussed in detail in the literature; a survey is given in De Boer (ed.) (1967); Van Bommel & de Boer (1980).
For roads without overhead lighting that have to be lit by vehicle headlamps only, the situation is much less favourable. As most of the light is reflected away from the source (the headlamp) the road surface will be very dark indeed. The contribution of light from opposing vehicles may help a little but it increases the disturbance in the field of view as well - and of course it increases glare quite considerably.

As the visibility of road markings is determined to a large extent by the contrast between the marking itself and its immediate surroundings (the road surface) a dark surface could be advantageous as regards the visibility of the markings provided of course that the markings do, contrary to the road, keep their high luminance. At the other hand it does not seem to be a wise decision to make road surfaces dark and shiny in order to increase this contrast in dry and/or wet conditions. It can be shown, and it follows to a certain extent also from the discussions in the preceeding sections of this report, that the road surface itself must as be visible as well, and should stay so (Padmos, 1984; Padmos & Walraven, 1982; Walraven, 1980; Schreuder, 1984). This point has been raised several times when discussing the possible disadvantages of portland cement-concrete roads as regards the ensuing reduction in the visibility of road markings. As was explained by o.a. Schreuder (1985d) the effect is real but there are many ways to enhance the contrast. More recently the same question was raised when considering the use of light (artificial) aggregates in road surfaces to enhance the luminance. Particularly as these roads may have favourable characteristics in other aspects as well, the matter was considered in some detail. Again here the conclusion is that the wet night visibility is the more important, and that the day and dry visibility of the markings can be ensured all the same (see e.g. SCW, 1974, 1982, 1984; Burghout, 1977, 1977a; Schreuder, 1982a).

7.2.2. Requirements for road markings in wet conditions

The functional requirements are defined and assessed in such a way that they do not depend upon the conditions. As regards the photometrical requirements this is different. In other words, the markings should be designed and applied in such a way that the functional requirements can be met also under wet conditions.

When the road surface including the markings attached to it, becomes wet, a layer of water spreads over both. The result on the visibility depends on the thickness of that layer. When the layer is so deep that all surface elements of road and marking are drowned, the reflection of the surface will be determined exclusively by the water itself, independent on what is under the water, particularly when one considers the situation and the geometry of observation relevant for car drivers. The usual eye height of drivers of passenger cars is some 1.2 m, and sometimes even lower. For drivers of vans and trucks this is higher, sometimes considerably higher. Still, when looking ahead some or several tens of meters the angle between the direction of observation and the surface is only small - one looks at a glancing angle. Under these circumstances one cannot look "into" the water as a pedestrian might be able to do: it is not possible to see what is under the water. The surface is inundated.

When the amount of water is less, the layer is correspondingly thinner. The larger elements of the road surface and of the road markings may protude over the water surface, so that they are visible even under the prevailing glancing angle of observation. Still they are wet; a water layer still clings to the surface and the actual things underneath cannot be seen. All one may be able to see is the structure of the surface of the water, that follows the structure of the surface underneath. The visibility is governed by the geometry of the surface (of road and marking combined) and not by the characteristics of the materials underneath the water - the colour, the reflection properties etc. This can be explained as follows.

The overall angle of observation is small. This implies that water, as all transparent materials, will reflect incident light nearly completely - more or less as a mirror. The light that reaches the eye at a small angle with the horizontal (the glancing angle of observation) must inping on the surface at the same small angle; all is reflected towards the eye, but it is reflected by the top surface of the water layer and will therefore not be affected by the optical characteristics of the stuff underneath. Differences between parts of the surface (e.g. between markings and road surfaces) can be discerned only if the difference in texture between the two is large enough - irrespective of the actual colour. A large difference in texture seems therefore to be preferable. Only when the surface is structured in such a way the light inpinges on it at a large angle (nearly perpendicular) the light may penetrate in the water and may therefore transmit towards the observer information regarding the stuff underneath the water - the principle on which the profiled road markings that are discussed furtheron, are based. As the light is reflected by the top surface of the water layer, the structure of that layer can be observed. From this follows the principle to ensure (at least some) visibility of road markings for unlit roads, both dry and wet: take care that there is a considerable difference in the texture of the two contrasting surfaces - the road and the marking. However, for roads with public lighting, this is not always true as, particularly when the difference is large, situations may occur when the markings are quite invisible (see Schreuder, 1965).
This was worked out for the markings of pedestrian crossings ("zebra crossings") by Schreuder (1962, 1964a, 1965). In this respect, traditional road paint is not favourable, as by applying paint the overall structure of the (road) surface is not changed. This is in agreement with practical experience: in dry, day conditions paints perform reasonable and sometimes even quite good, but in other - less favourable - conditions they are often not up to standard (see Sec. 7.2.3).

7.3.3. Wet night visibility of road markings

Road markings are invisible on wet roads without public lighting at night (independent on their visibility in dry condition or at day) unless they have vertical elements perpendicular to the direction of driving and facing the traffic.
This statement contains the result of a considerable amount of research and practical experience (see CIE, 1983; OECD, 1975; SCW, 1982; Schreuder, 1985; Serres, 1978 etc.). The reason for this has been explained in the foregoing sections: unless the light can penetrate in the water on top of the surface, it is nothing but the water that reflects the light. And that does not contribute to the visibility to any appreciable extent, particularly on unlit roads (roads without public lighting).

As explained earlier this is the case for all types of surface. Obviously it is the case as well for retro-reflecting surfaces; in fact, it is even much more the case, as in dry condition (when the light can penetrate into the interior of the device, where the retro-reflection is taking place) such devices have a reflection that is much a higher that than any diffuse surface could reach. One might say that retro-reflecting devices show a reflection factor higher than the unity - in fact much higher. In order to avoid confusion, the concept of reflection factor is not used to describe the reflection of retro-reflectors. It might be added here that there is some confusion as to what should be used in stead (CIE, 1983).

In three countries extensive experiments were made in order to assess the wet night visibility of road markings by means of large, full scale trials under actual road traffic conditions: the U.S., the Netherlands and the Federal Republic of Germany. To these three groups of experiments a large number of more restricted studies may be added (see e.g. Schreuder, 1980, 1981a, 1985).

The three major studies were similar in approach: on a normal road (sometimes a number of different roads) a large number of different roadmarking materials was applied. These were studied for a considerable time under different conditions of weather, traffic and lighting. The study included photometric and colorimetric measurements and a subjective assessment of day and night visibility under the different relevant weather and lighting conditions, concentrating on the wet night visibility on unlit roads. The studies are complete, but the results are not completely published: reports are still in preparation. See for the U.S. study: Tooke & Hurst (1975); for the studies in the Netherlands: SCW, 1982, 1985; Schreuder, 1985; Van Gorkum, 1982, 1983, 1984, 1984a; Blaauw et al. 1984; Blaauw & Padmos, 1979, 1981, 1982; Clee & Hogervorst, 1981; and for the German study: Schreuder, 1980; Domhan, 1982; Hiersche & Tenzinger, 1984 and Neis (1985). A smaller but simular study has been made in France, see Krauze (1979, 1984) and Serres (1978).

The materials compared were different in the different studies. The reason is primarily that for obvious reasons one did concentrate on materials that were available and sometimes even in use in the different countries; furthermore there is a considerable time difference between the three studies. In view of the rapid developments in this area, this resulted as well in the study of different materials.
The U.S. study included paint, standard and corrugated (profiled) thermoplasts, light aggregates and raised pavement markers (studs) with prismatic retro-reflecting devices. All paints and plastic materials were "beaded": they included glass lenses or spheres (glass beads). The Dutch study included paint and standard and profiled thermoplasts (all beaded), and a number of different raised pavement markers with different types of retro-reflectors. Finally the German study did not include raised pavement markers, but it did include many types of profiled marking materials, some of them formed-in-place thermoplasts and others pre-formed sheet type materials. Again all were beaded. To this a number of special lens type beads were included; many of the materials tested in the German study were experimental. Several of the materials included in these tests, particularly in the German test, have been made available in the mean time. A number of them were shown at the Intertraffic Exhibition '86 (Anon, 1986), notably the small reflectorized dots (Anon, 1986b, c) and miniature reflectorized road studs included in the standard road marking stripes (Anon, 1986d), see also Anon (1980a). Another solution is given in Anon (1986g).

The results of the three studies are very much in mutual agreement; they can be summarized in the statement at the beginning of this section. It is possible to elaborate on this.

The studies of the U.S. and the Netherlands did agree in another aspect. It is possible to "rank" the different materials and devices according to their visibility under different conditions, yielding a ranking order of merit. In both studies it was found that, in dry daylight conditions the order of merit was (from high to low): paint-thermoplast-white aggregate-profiled markings-raised pavement markers with prismatic retro-reflectors.
Contrary to this, it was found that at night on wet surface with vehicle-headlamp lighting the order of merit was exactly the opposite. This implies that paints that perform quite good at day are useless when wet at night; and that raised pavement markers with prismatic retroreflectors, that perform excellent at night even when wet are poorly visible at day when dry.

The German study did not include raised pavement markers, but a similar effect was found: in all cases profiled markings performed much better than non-profiled markings when wet but at day, non-profiled markings like paint were often superior. And more in particular it was found that profiled markings that show (near) vertical planes facing the traffic are by far the better as regards the wet night visibility on unlit roads.
The different studies did include a great number of other tests and measurements. They will not be repeated here; the results can be found in the research reports and the publications quoted above. One exception, however. It was clearly shown that raised pavement markers and profiled road markings do not cause danger for motorcyclists. They may, however, cause considerable discomfort (Wildervanck, 1981, 1982).

7.2.4. Conclusion

The final conclusion is that it is quite feasible to design and apply a road marking that is visible under the combined unfavourable conditions of wet road surface, darkness and absence of public (overhead) lighting. The statement at the beginning of Sec. 7.2.3. indicates how to do it.

It might be added that many of the solutions to this problem that were studied could withstand heavy traffic for many years and frequent snow-plowing as well. The problem is, however, the fact that the markings that perform best under these adverse conditions are not the best in dry daylight conditions; conditions that are less unfavourable but that are more frequent.

8. RECOMMENDATION

We will conclude this report of the first phase of the project with the statement that follows directly from this: it is necessary to design and develop road marking materials or devices that perform equally well under different conditions. Such materials or devices might possible be of the "hybrid" type! It is proposed to have this study followed by further studies.

TABLES AND FIGURES

Table I. Listing of manoeuvres (after Schreuder, 1974).

Table IIa. Stopping distance (in m) for different speed V (m/s) verall reaction time (s) ans retardation a (m/s^2).

Table IIb. Minimum stopping sight distance. (Quoted from: Baerwald (ed.), 1965, p. 30).

Table III. Relevant objects and their preview requirements (after Schreuder, 1985b).

Figure 1. Coefficients of retro-reflection for all experimental markings on a wet pavement as a function of the time after sprinkling. Ultimate values, as measured on the dry pavement, are given on the right axes (Quoted from Blaauw & Padmos, 1981).

Figure 2. Predicted visibility distances immediately after application, for all markings on dry and wet pavement. Distances are calculated good atmospheric conditions (Z = 15 km) and for new and practice values of the headlamp intensities. The distances are based on the measured retro-reflection coefficients. Requirements for minimum visibility distance are given for rural roads with V_{85} velocities of 80 and 100 km/h (Quoted from: Blaauw & Padmos, 1981).

ELEMENTARY MANOEUVRES

* "just going on"
* swerving around
* changing lanes
* changing (reducing) speed
* stopping

COMPLEX MANOEUVRES

* "just going on"
* pass a discontinuity
* cross a (priority) intersection
* negotiate a curve
* pass a change of roads
* change direction e.g. on an intersection
* leave the road (change direction and road type)
* overtaking and passing
* overtaking and passing with opposing traffic
* meet queing traffic
* avoid conflicts
- with pedestrians
- with (pedal) bicycles
- with slow traffic
- with fast traffic (cars etc.)
* being confronted with obstructions
* reaching the destination

Table I. Listing of manoeuvres (after Schreuder, 1974).

a	v = 10 m/s (36 km/h)					v = 15 m/s (54 km/n)				
m/s^2	t = 1	2	3	6	10	1	2	3	6	10
1	60	70	80	110	150	127	142	157	202	262
1,5	43	53	63	93	133	90	105	120	165	225
2	35	45	55	85	125	71	86	101	146	206
3	26	36	46	76	116	52	67	82	127	187
4	22,5	32,5	42,5	72,5	112,5	43	58	73	118	178
5	20	30	40	70	110	37	52	67	112	172
6	18	28	38	68	108	34	49	64	109	169
8	16	26	36	66	106	29	44	59	104	164

a	v = 20 m/s (72 km/h)					v = 30 m/s (108 km/h)				
m/s^2	t = 1	2	3	6	10	1	2	3	6	10
1	220	240	260	320	400	480	510	540	630	750
1,5	153	173	193	253	333	330	360	390	480	600
2	120	140	160	220	300	255	285	315	405	525
3	87	107	127	187	267	180	210	240	330	450
4	70	90	110	170	250	142	172	202	292	412
5	60	80	100	160	240	120	150	180	270	390
6	53	73	93	153	233	105	135	165	255	375
8	45	65	85	145	225	86	116	146	236	256

Table IIa. Stopping distance (in m) for different speed v (m/s) overall reaction time t (s) and retardation a (m/s^2).

Operating speed (mph)	Pavement condition					
	Wet			Dry		
	Perception -reaction distance (ft)	Braking distance (ft)	Total distance (ft)	Perception -reaction distance (ft)	Braking distance (ft)	Total distance (ft)
30	110	86	196	110	43	159
40	148	167	315	148	89	237
50	183	278	461	183	144	327
60	220	414	634	220	214	434
70	258	583	841	258	298	556

Source: Policy on Geometric Design of Rural Highways, American Association of tate Highway Officials, Washington, D.C., 1954, p. 115 (slightly modified to indicate distances for operating speed rather than design speed).

Table IIb. Minimum stopping sight distance. (Quoted from: Baerwald (ed.), 1965, p. 30).

Task aspect	Preview (metres)		Object
Manoeuvre	High speed	Low speed	
* Route selection	many hundreds	several hundreds	road, road characteristics
* Complex manoeuvre	several hundreds	many tens	
* Elementary manoeuvre			
. stopping	several hundreds	many tens	road signs,
. other	many tens	several tens	road markings
* Manoeuvre parts	several tens	about ten	
* Other traffic			
. cars	several hundreds	many tens	other road
. other	many tens	several tens	user
* Task II			
. stopping	many tens	several tens	road, road markings
. changing lanes	several tens	about tens	+ other users +
. swerving	about tens	several metres	obstacles

Table III. Relevant objects and their preview requirements (after Schreuder, 1985b).

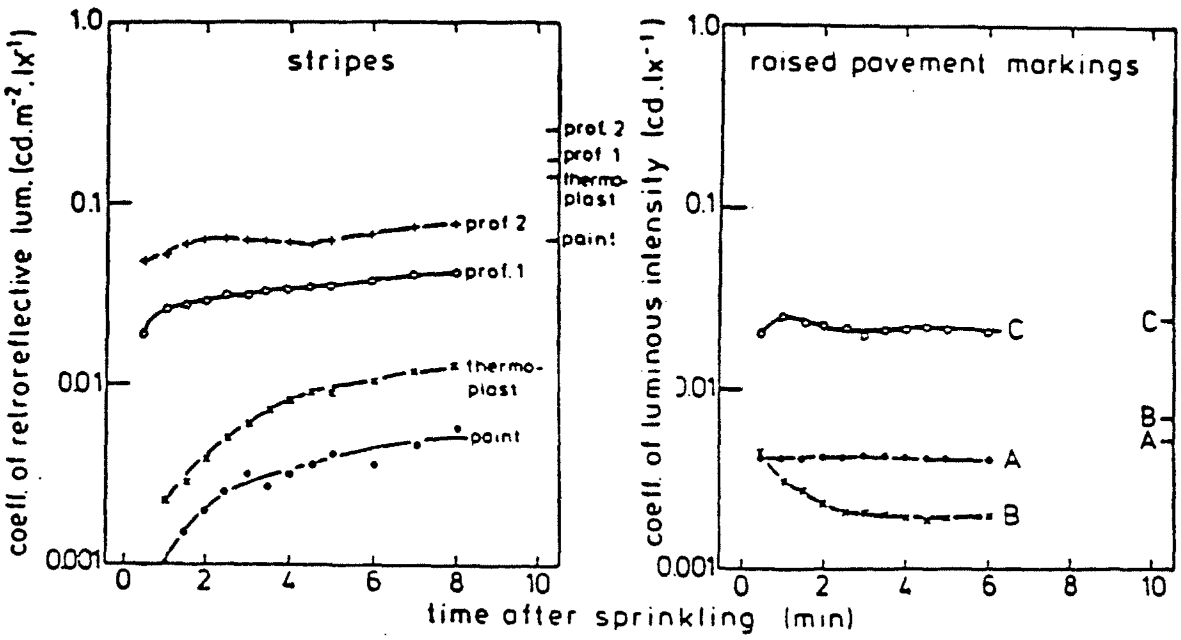

Figure 1. Coefficients of retro-reflection for all experimental markings on a wet pavement as a function of the time after sprinkling. Ultimate values, as measured on the dry pavement, are given on the right axes (Quoted from Blaauw & Padmos, 1981).

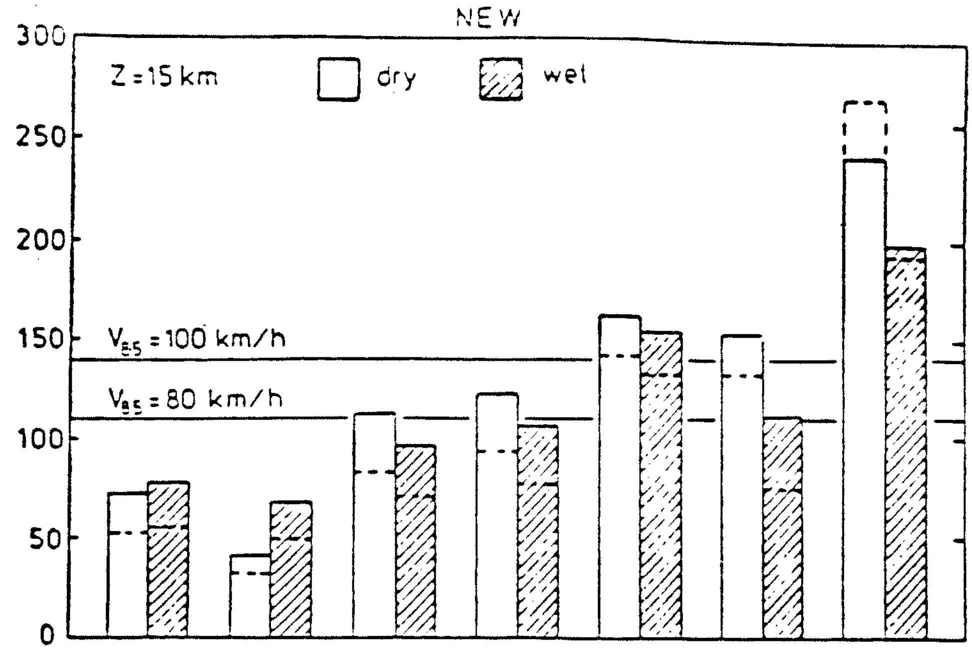

Figure 2. Predicted visibility distances immediately after application, for all markings on dry and wet pavement. Distances are calculated good atmospheric conditions (Z = 15 km) and for new and practice values of the headlamp intensities. The distances are based on the measured retro-reflection coefficients. Requirements for minimum visibility distance are given for rural roads with V_{85} velocities of 80 and 100 km/h. (Quoted from: Blaauw & Padmos, 1981).

REFERENCES

- Adams, G.H. (1976). Highway markings - a bibliography with abstracts. Report PS-76/0294. NTIS, Springfield, Va, 1976.
- Adrian, W. (1976). Method of calculating the required luminances in tunnel entrances. Lighting Res. & Technol. 8 (1976) 103-106.
- Adrian, W. (1980). Investigations on the required luminance in tunnel entrances. Conference paper, CIBS Annual Conference, Canterbury, 1980 (Not published).
- Allen, M.J. (1970). Vision and highway safety. Chilton, 1970.
- Allen, R.W. et al. (1977). Driver's visibility requirements for roadway delination; Vol I: Effects of contrast and configuration on driver performance and behaviour. Final Report FHWA-RD-77-165. Systems Technology, Inc., Hawthorne, Cal., 1977.
- Anon (1959). Visuele problemen van het wegverkeer (Visual problems of road traffic). Het Nederlandse Wegencongres, Den Haag, 1959.
- Anon (1972). Intertraffic 1972. International Congress on traffic engineering, 26 May, 1972. RAI, Amsterdam, 1972.
- Anon (1974). Wegontwerp en wegverlichting tegen de achtergrond van de verkeersveiligheid (Road design and road lighting in relation to road safety). Pre-adviezen congresdag 6 december 1974. Het Nederlandse Wegencongres, Den Haag, 1974.
- Anon (1979). Traffic guidance and road safety: The role of carriageway markings. Highways and Public Works 47 (1979) (Dec.).
- Anon (1980). Geprofileerde wegmarkingen en markeerknopen lijken voordelen te hebben (Profiled road marking seem to be advantageous). SWOV-schrift 6 (dec. 1980): 4-5.
- Anon (1980a). Vorrichtung zur Herstellung von Markierungen auf Fahrbahnen. Gebrauchsmuster GM 8021172. Deutsches Patentamt, 1980.
- Anon (1981). De "porous friction course". Wegen 55 (1981) 271-278.
- Anon (1982) Scotchlite veiligheid (Scotchlite safety). Product information. 3M Nederland BV, Leiden, 1982 (year estimated).
- Anon (1984). "Rumble strips" cut road accident rate. World Highways (1984) 3: 3.
- Anon (1985). Zichtbaarheid 's nachts van wegmarkeringen op droge en natte wegdekken (Night visibility of road markings on dry and wet roads). (Ontwerp Eindmededeling in voorbereiding). Stichting Studiecentrum Wegenbouw SCW, Arnhem, 1985.

- Anon (1985a). Geluidsniveauverhoging door wegmarkeringen. (Increase in noise level from road markings). WOM-G-85-03e (Not published).
- Anon (1986). International exhibition Intertraffic 1986. RAI, Amsterdam, 1986.
- Anon (1986a). Fibre optic lane marker unit. Product information, Stone Chance, Crawley. In: Anon (1986).
- Anon (1986b). Spotflex. Product information, Superfos, Vedbaek. In: Anon (1986).
- Anon (1986c). Spotflex, de extra veilige makering (Spotflex, the extra safe marking). Product information, Heymans, 's-Hertogenbosch. In: Anon, 1986.
- Anon (1986d). Plastic reflective road stud. Product information. Swarovski, Wattens. In: Anon (1986).
- Anon (1986e). Tesalux Ultralite. Product information, Beiersdorf AG, Hamburg. In: Anon (1986).
- Anon (1986f). Reflexite, microprism retro-reflective material. Product information, Reflexite corporation, Europe, Copenhagen. In: Anon (1986).
- Anon (1986g). Embossed pavement-marking sheet material. European patent 2/EP 0093 495 B1 (published 27-11-1985). Minnesota Mining and Manufacturing Company, St. Paul, MN, 1986.
- Asmussen, E. (1972). Transportation research in general and travellers' decision making in pedestrian as a tool for transportation management. In: OECD (1972).
- Asmussen, E. (1974). Functionele eisen van een toekomstige verkeerssysteem (Functional requirements of a future transport system). R-74-75. SWOV, 1974.
- Asmussen, E.; Kranenburg, A. (1982). An analysis of the traffic safety phenomenon. Publication 1982-1E. SWOV, 1982.
- Attwood, D.A. (1976). Effects of headlight intensity and ambient illumination of two-lane passing behaviour. Int. Ergonomics Association. Human Factors Soc., Santa Monica, 1976.
- Baerwald, J.E. (ed) (1965). Traffic engineering handbook, 3rd ed. ITE, Washington, D.C., 1965.
- Bernhard, M. (1984). Road signs in Europe. In: TRB (1984).
- Blaauw, G.J. (1984). Car driving as a supervisory control task (Thesis). Technische Hogeschool, Delft, 1984.

- Blaauw, G.J.; Buist, M.; Burrij, S.; Hoogewerf, F. (1984). De geleidingsfunctie van markeringsgeometrieën bij nacht. IZF 1984-C4. (concept). IZF-TNO, Soesterberg, 1984.
- Blaauw, G.J. & Padmos, P. (1979). Zichtbaarheid van wegmarkeringen op natte wegen bij nacht; Evaluatie van een meetmethode (Night visibility of road markings on wet roads; evaluation of a measuring method). Memo 1979-M7. IZF-TNO, Soesterberg, 1979.
- Blaauw, G.J. & Padmos, P. (1981). De zichtbaarheid 's nachts van wegmarkeringen op droge en natte wegen (Night visibility of road markings on dry and wet roads). IZF 1981-C20. IZF-TNO, Soesterberg, 1981.
- Blaauw, G.J. & Padmos, P. (1982). Nighttime visibility of various types of road markings; A study on durability, including conditions of rain, fog and dew. SAE paper 820412. SAE, Detroit, Mich., 1982.
- Blaauw, G.J. & Padmos, P.; Alferdinck, J.W.A.M.; Hoogewerf, F. (1983). De zichtbaarheid 's nachts van negen vertikaal geprofileerde wegmarkeringen op droge en natte wegen. IZF 1983-C24. IZF-TNO, Soesterberg, 1983.
- Blaauw, G.J.; Riemerma, J.B.J. (1975). Interpretation of roadway design by an analysis of drivers' visual scanning and driving behaviour on straight and curved roadway section. Report No. 1975-C5. IZF-TNO, Soeterberg, 1975.
- Blackwell, H.R. (1946). Contrast thresholds of the human eye. Journ. Opt. Soc. Amer. 36 (1946) 624-643.
- Blackwell, H.R. (1959). Development and use of a quantative methode for specification of interior illumination levels on the basis of performance data. Illum. Engng. 54 (1959) 317-353.
- Blokpoel, A.; Schreuder, D.A.; Wegman, F.C.M. (1982). De waarneembaarheid bij duisternis van de zijkant van fietsen. R-82-36. SWOV, 1982.
- Böcher, W. (1975). Vorsicht-Umsicht-Rücksicht. Kirschbaum Verlag, Bonn-Bad Godesberg, 1975.
- Bonnet, G.; Poilane, J.P. (1985). Le drainage des structures de chaussées autoroutières en dalle épaisse. Bull. Liaison Labo. P et Ch 140 (1985) nov. - dec., p. 7-17.
- Broadbent, D.E. (1958). Perception and communication. Pergamon Press, London, 1958.
- Bry, M. (1985). Comment ont contitués les produits de marquage de chaussées? Bull. Liaison Labo P et Ch 140 (1985) Nov.-Dec., 47 - 51.

- Bryden, J.E. (1981). Pavement-marking materials. The State of the art, The Quarterly R & D Digest, No. 16. Summer 1981.
- Burghout, F. (1977). Kenngrössen der Reflexionseigenschaffen von trockenen Fahrbahndecken. Lichttechnik 29 (1977) 23-27.
- Burghout, F. (1977a). Simple parameters significant of the reflection properties of dry road surfaces. In: CIE (1977).
- Cahoon, R.L. & Cruz, B.E. (1970). Use of a rumble strip to reduce maintenance and increase driving safety. Final report 1969. State Dept. of Highways, Utah, 1970.
- Capelli, J.T. (1973). Audible roadway delineators. New York State Dept. of Transportation, Albany, 1973.
- Chandler, K.N. (1954). The theory of corner-cube reflectors. Research Note No. RN/2267/KNC. Road Research Laboratory, 1954.
- Chandler, K.N. (1954a). The theory of a lens-type reflector. Research Note No. RN/2266/KNC. Road Research Laboratory, 1954.
- CIE (1972). A unified framework of methods for evaluating visual performance aspects of lighting. Publication No. 19. CIE, Paris, 1972.
- CIE (1974). Standpoint on the utilisation of low-beam headlamps by vehicles in built-up areas. CIE, Paris, 1974.
- CIE (1977). Measures of road lighting effectiveness; Symposium, July 5-6, 1977. LiTG, Karlsruhe, 1977.
- CIE (1980). Proceedings 19th session Kyoto, 1979. Publication No. 50. CIE, Paris, 1980.
- CIE (1981). An analytic model for describing the influence of lighting parameters upon visual performance. Publication No. 19/2. CIE, Paris, 1981.
- CIE (1982). Retroreflection - definition and measurement. Publication No. 54. CIE, Paris, 1982.
- CIE (1983). International symposium Visual aspects of road markings, Paris, 2-3 May 1983. Reports and papers. CIE, Paris, 1983.
- CIE (1984). Properties and uses of retroreflectors at night. (Draft technical report). CIE, 1984.
- CIE (1985). Visual aspects of road markings. (Draft technical report). CIE, 1985.
- CIE (1986). Road signs (Draft technical report). CIE, 1986.
- Clee, H. & Hogervorst, D. (1981). Road markings: Testing and application in the Netherlands. Publication 36. Rijkswaterstaat, 1981.

- Creech, M.F. (1976). Installation of fog guidance lights on Afton Mountain. VHTRC 77-R12. Virginia Highway & Transportation Research Council, Charlottesville, Vir., 1976.
- De Boer, J.B. (1951). Fundamental experiments of visibility and admissible glare in road lighting. CIE, Stockholm, 1951.
- De Boer, J.B. (1955). A "duplo" headlight with asymmetric passing beam. Light & Lighting 68 (1955) No. 4.
- De Boer, J.B. (ed.) (1967). Public lighting. Centrex, Eindhoven, 1967.
- De Boer, J.B. & Morass, W. (1956). Berechnung der Sehweite aus der Lichtverteilung von Automobilscheinwerfer. Lichttechnik 8 (1956) 433-437.
- De Boer, J.B. & Schreuder, D.A. (1969). Betrachtungen über die Anwendung von Halogenscheinwerfer für die Kraftfahrzeugbeleuchtung. Lichttechnik 21 (1969) 88A-92A.
- Domhan, M. (1982). Probleme der optischen Führung bei Nacht und Nässe. Strassenverkehrstechnik 26 (1982) 153-158.
- Douglas, C.A. & Booker, R.L. (1977). Visual range: concepts, instrumental determination, and aviation application. NBS Monograph 159. National Bureau of Standards, Washington D.C., 1977.
- Dutruit, M. (1974). Die Retro-Reflexion. Regionale Strassen Konferenz IRF, Budapest, 1974.
- Dutruit, M. (1980). Up-to-date road signing and traffic safety. In: IRF (1980).
- Ebell, R.J.E.V.; Groot, R.E.; Schreuder, D.A. & Theewis, S.R. (1984). Probleemanalyse visuele waarneembaarheid van kruisende fietsers en bromfietsers bij duisternis in relatie tot een RVLV-maatregel. IWACC 1984-1 (twee delen). IWACC, Oudendijk, 1984.
- Ebell-Vonk, E.M. et al. (1983). Inventarisatie: Visuele waarneembaarheid van tweewielers. IWACC 1983-1. IWACC, Oudendijk, 1984.
- Economopoulos, I.A. (1977). Relationship between lighting parameters and visual performance in road lighting. In: CIE (1977).
- Emde, W. et al. (1985). Kostensätze für die volkswirtschaftliche Bewertung von Strasenverkehrsunfällen - Preisstand 1985. Strasse und Autobahn (1985) 159-162.
- Farrimond, K.D. (1968). Use of a rumble stripe to reduce maintenance and increase driving safety. Research Report 500-901. State Dept. of Highways, Utah, 1968.
- Fisher, J. (1970). Lighting on vehicles: Design for safety and comfort. Illum. Engng. Soc. Australia, 1970.

- Fisher, A.J. (1970a). A basis for a vehicle headlighting specification. Lighting Review (Sydney) 32 (1970) 9.

- Fisher, A.J. & Hall, R.R. (1970). Road user reaction to the town driving headlight beam. Proceedings No. 5 pt 3, p. 252-263. Australian Road Research Board, Melbourne, 1970.

- Forsberg, A. (1978). Optical guidance in darkness on roads without public lighting (In Swedish). Nr. 152-1978. National Road and Traffic Research Institute VTI, Linköping, 1978.

- Frybourg, M. (1972). L'aide à la conduite et le marquage des chaussées. In: Anon (1972).

- Gallagher, V.P.; Janoff, M.S.; Blubaugh, J.G. & Vetere, P.L. (1972). Interaction between fixed and vehicular illumination systems. Intern Report on Phase II. FHWA-RD-72-23. Franklin Institute, Philadelphia, Penn., 1972.

- Gallagher, V.P.; Janoff, M.S. & Faber, E. (1974). Interaction between fixed and vehicular illumination systems on city streets. Journal of IES 4 (1974) 3-10.

- Gallagher, V.P.; Schwab, R.N. & Janoff, M.S. (1977). Implementing a roadway lighting system based on the visibility index concept. In: CIE (1977).

- Gillis, H.J. (1980). Durable pavement marking materials study (year estimated). Research and Development 80-08-49. Department of Transportation. Minnesota, 1980.

- Godthelp, J. (1984). Studies on human vehicle control. (Thesis). Technische Hogeschool, Delft, 1984.

- Godthelp, J. & Riemersma, J.B.J. (1982). Vehicle guidance in road-work zones. Ergonomics 25 (1982) 909-916.

- Godthelp, J. & Riemersma, J.B.J. (1982a). Perception of delineation devices in road work zones during nighttime. SAE Paper 820413. SAE, Detroit, 1982.

- Goerner, E.W. (1986). Schrifttum Fahrbahnmarkierungen 1980-1984. Heft 6, 1986. Schriftenreihe der deutschen Studiengesellschaft der Hersteller von Markierungsglasperlen (DSGM). Essen, 1986.

- Gramberg-Danielsen, B. (1967). Sehen und Verkehr. Springer Verlag, Berlin, 1967.

- Harrigan, E.T. (1977). New materials and systems for improved traffic delineation. Public Roads 41 (1977) (cit.: OECD, 1980).

- Hauer, E. (1986). On the estimation of the expected number of accident. Accid. Anal. & Prev. 18 (1986) 1-12.
- Hemion, R.H. (1969). Disability glare effects during a transition to polarized vehicle headlights. Report AR-672. Southwest Research Institute, San Antonio, 1969.
- Hiersche, E.-V. & Tenzinger, B. (1984). Inventarisierung und Beurteilung von Fahrbahnmarkierungen im Ausland. Strassenverkehrstechnik 28 (1984) 88-89.
- Hofman, F. (1979). Verbesserung der Nacht-Nass Sichtbarkeit von Strassenmarkierungen. Strassenverkehrstechnik 23 (1979) 161-163.
- Hopkins, T.A.; Marshall, B.R. (1974). Feasibility study of luminescent pavement markers; criterium report. NASA, Greenbelt, Md, 1974 (Quoted by Adams, 1976).
- ILE (1986). Light for lives. European road safety year symposium, 16 april 1986. Institution of Lighting Engineers, Birmingham, 1986.
- IWACC (1983). Fietsverlichting en fietsreflectoren (overige). IWACC 1983-IV. (Bijlage bij Ebell-Vonk et al. (1983).
- IWACC (1983a). Mengverkeer, visuele waarneming en beleid. IWACC 1983-V. (Bijlage bij Ebell-Vonk et al. (1983).
- Jacobs, S.F. (1982). Experiments with retrodirective arrays. Optical Engng. 21 (1982) no. 2, 281-283.
- James, J.G.; Hayward, A.T.J. (1960). A note on the principle of reflectorised road-marking materials. Roads & Road Construction 38 (1960) 122-123.
- Janssen, W.H. (1984). De detectie van een mogelijke botsing bij gebogen nadering van een kruispunt (The detection of inpending collision in intersections with curved approaches). IZF 1984-C3. IZF-TNO, Soesterberg, 1984.
- Janssen, W.H. & Van der Horst, A.R.A. (1980). The perception of inpending collision in night-time driving. IZF 1980-C17. IZF-TNO, Soesterberg, 1980.
- Jackson, J. (1981). Safety measures: The contribution of carriageway markings. The Highway Engineer (1981) (Febr.) 2-5.
- Jackson, J. (1983). Reflectorized road markings their contribution to traffic safety. In: CIE (1983).
- Johansson, G. & Rumar, K. (1968). Visible distances and safe approach speeds for night driving. Ergonomics 11 (1968) 275-282.

- Jonkers, G.H. (1986). Ogen en keuringseisen (Eyes and test requirements). In: VVAA (1986).
- Kamplade, J. (1981). Untersuchungen über die Verkehrssicherheit bei Nässe. Strasse u. Autobahn 8 (1981).
- Kenton, E. (1978). Highway markings - a bibliography with abstracts. NTIS/PS - 78/0393. US Dept. of Commerce, Springfield, Va (1978).
- Krauze, D. (1979). Visibilité de nuit des marquages routiers par temps de pluie. PV 79.568. Laboratoire Regional de Saint Quentin, 1979.
- Krauze, D. (1984). Etude de la signalisation horizontale; Visibilité de nuit par temps de pluie de marquages expérimentaux appliqués en rive sur chaussée circulée. PV 84-194. Laboratoire Regional de Saint Quentin, 1984.
- Lorenz, H. (1971). Trassierung und Gestaltung von Strassen und Autobahnen. Bauverlag GMBH, Wiesbaden, Berlin, 1971.
- Mackaulay, N.S. (1986). Road lighting in the United Kingdom. In: ILE, 1986.
- Matanzo, F. & Rockwell, T.P.H. (1967). Driving performance under nighttime conditions of visual degradation. Human Factors 9 (1967) 427-432.
- Meseberg, H. (1985). Uberprüfung der Erkennbarkeit von Fahrbannmarkierungen auf aufgehellten Deckschichten. Forschungsauftrag Nr. 350 (3.027B74B). Bundesanstalt für Strassenwesen, Bergisch Gladbach, 1985.
- Michon, J.A. (1979). Dealing with danger. VK 79-01. Verkeerskundig Studiecentrum, Groningen, 1979.
- Michon, J.A.; Eijkman, E.G.J. & De Klerk, L.F.W. (eds.) (1979). Handbook of psychonomics (2 volumes). North-Holland Publishing Company, Amsterdam, 1979.
- Middleton, W.E.K. (1952). Vision through the atmosphere. Toronto Press, Toronto, 1952.
- Moon, P. (1961). The scientific basis of illumination engineering (rev. ed.). S. 242. Dover, New York, 1961.
- Mortimer, R.G. (1971). Hard braking is more common than you might think. Automotive Engng. (1971) Aug.; p. 32
- Neis, H. (1985). Zur Problematik der Erfassung und Beurteilung von profilierten Fahrbahnmarkierungen in trockenem und nassem Zustand. Dissertation D. 7. TH, Darmstadt, 1985.
- Noordzij. P.N.; De Loor, H.M.; Rothengatter, T.A. & Kuiken, M.J. (1985). Voorrangsgedrag en verkeersveiligheid (Priority behaviour and road safety). Werkgroep Veiligheid /R-85/1. Leiden, University, 1985.

- OECD (1972). Symposium on road user perception and decision making (In Italian). OECD, Rome, 1972.
- OECD (1975). Road marking and delineation. OECD, Paris, 1975.
- OECD (1976). Adverse weather, reduced visibility and road safety. OECD, Paris, 1976.
- OECD (1979). Improving road safety at night. OECD, Paris, 1979.
- OECD (1984). Integrated road safety programmes. OECD, Paris, 1984.
- OECD (1984a). Road surface characteristics: Their interaction and their optimisation. OECD, Paris, 1984.
- O'Flaherty, C.A. (1972). Delineating the edge of the carriageway in rural areas. International Road Federation, Washington, D.C., 1972.
- O'Hanlon, J.F. (1983). Raised lane-line pavement markers as an aid to the performance of impaired drivers (Abridgement). In: CIE (1983).
- Oppe, S. (1985). Hoorzitting mistongeval Leiderdorp. SWOV, Leidschendam, 1985. (Not published).
- OTA (1970). Tenth International Study Week in Traffic and Safety Engineering. OTA, Rotterdam, 1970.
- Overdijkink, G.A, (1959). Beplanting en optische geleiding (Vegetation and optical guidance). In: Anon (1959).
- Paar, H.G. (1975). De relatie tussen de stroefheid van wegdekken en de ongevallenkans (The relationship between skidding resistance of road surfaces and accidents). Verkeerstechnische Leergang 1973. ANWB, Den Haag, 1975.
- Padmos, P. (1984). Visually critical elements in night driving in relation to public lighting. In: TRB (1984).
- Padmos, P. & Walraven, J. (1982). Wegverlichting buiten de bebouwde kom: welke visuele informatie heeft de automobilist nodig? Lezing Congresdag op 23 april 1982 "Openbare verlichting - economie en veiligheid". NSVV, Amsterdam, 1982.
- Reid, J.A.; Sabey, B.A.; James, J.G. (1962). White-line road-markings and light-coloured road surfacings. J. Appl. Chemistry 12 (1962) 201-217.
- Riemersma, J.B.J. (1979). The perception of deviation from a straight course. IZF 1979-C6. IZF-TNO, Soesterberg, 1979.
- Riemersma, J.B.J. (1979a). The perception of course and speed during locomotion; A review of some theoretical formulations. IZF 1979-C4. IZF-TNO, Soesterberg, 1979.
- Riemersma, J.B.J. (1983). Visual processes in vehicle guidance. In: CIE (1983).

- Riemersma, J.B.J. (1984). Driving behaviour in road curves; A review of the literature. IZF 1984-C12. IZF-TNO, Soesterberg, 1984.

- Riemersma, J.B.J. (1985). Koershouden op de rechte weg (Course holding on straight roads). Verkeerskunde 36 (1985) 367-372.

- Rockwell, T.H.; Ernst, R.L.; Rulon, M.J. (1970). Visual requirements in night driving. Rep. 99. National Cooperative Highway Research Programme. HRB, Washington (D.C.) 1970.

- Ross, N.F. & Russam, K. (1968). The depth of rain water on road surfaces. Report LR 236. Road Research Laboratory, Crowthorne, 1968.

- Roszbach, R. (1972). Some problems in the design of improved vehicle rear lighting configurations. In: SWOV (1971).

- Roszbach, R. (1974). Verlichting en signalering aan de achterzijde van voertuigen (Lighting and signalisation at the rear end of vehicles). R-74-11. SWOV, 1974.

- Rumar, K. (1970). Effectiveness of old, new and future motor-car lighting. In: OTA (1970).

- Rumar, K. (1974). Dirty headlights; Frequency and visibility effects. Ergonomics 17 (1974) 529-533.

- Sabey, B.E. (1968). The road surface and safety of vehicles. Proc. Inst. Mich. Engngs. Vol. 183, part A, 1968-69.

- Sabey, B.E. (1980). Road safety and value for money. Supplementary Report 581. TRRL, Crowthorne, 1980.

- Sanders, A.F. (1979). Performance theory, Chapter 8. In: Michon et al., eds. (1979).

- Saville, K.M. (1969). Experimental installation of rumble strips in Indiana. Purdue University Road School Proceedings 55 (1969) 62-78.

- Schlösser, L.H.M. (1975). Traffic accidents and road surface skidding resistance. R-75-1. SWOV, 1975.

- Schlösser, L.H.M.; Doornekamp, J. (1979). Ongevallen op natte wegdek (Accidents on wet roads). Verkeerskunde 30 (1979) 500-504.

- Schönborn, H.D. & Domhan, M. (1981). Handbuch für die Markierung von Strassen. Otto Elsner Verlag, Darmstadt, 1981.

- Schreuder, D.A. (1962). Aufgehellte Fahrbahndecken und lichttechnische Probleme. Asphalt- u. Teerstrassen 16 (1962) 144-153.

- Schreuder, D.A. (1964). The lighting of vehicular traffic tunnels. Centrex, Eindhoven, 1964.

- Schreuder, D.A. (1964a). Marking and lighting of pedestrian crossings. Intern. Lighting Rev. 15 (1964) 75-77.

- Schreuder, D.A. (1964b). Lighting in adverse weather. Traffic Engng. Contr. 5 (1964) 720-723.

- Schreuder, D.A. (1965). Reflectie-eigenschappen van wegmarkeringsmaterialen (Reflection properties of road marking materials). Wegen 39 (1965) 8: 186-191.

- Schreuder, D.A. (1967). Theoretical basis of road-lighting design. Chapter 3 In: De Boer (ed.), 1967.

- Schreuder, D.A. (1970). A functional approach to lighting research. In: OTA (1970).

- Schreuder, D.A. (1970a). Road lighting and traffic safety; A functional approach. Lux (1970) 57: 146-147; 256-263.

- Schreuder, D.A. (1972). The coding and transmission of information by means of road lighting. In: SWOV (1971).

- Schreuder, D.A. (1973). De motivatie tot voertuiggebruik (Motivation for vehicle use). Leidschendam, 1973.

- Schreuder, D.A. (1973a). Lichttechnische aspecten van een wegdek van cement-beton; enkele opmerkingen (Lighttechnical aspects of cement-concrete roads; Some remarks). Wegen 47 (1973) 23.

- Schreuder, D.A. (1974). De rol van functionele eisen bij de wegverlichting (The role of functional requirements in road lighting). In: Anon (1974).

- Schreuder, D.A. (1976). An integrated system for vehicle lighting and signalling. R-76-41. SWOV, 1976.

- Schreuder, D.A. (1976a). Voertuigverlichting binnen de bebouwde kom (herziene versie) (Vehicle lighting in built-up areas, revised edition). R-76-7. SWOV, 1976.

- Schreuder, D.A. (1977). The relation between lighting parameters and driver performance. In: CIE (1977).

- Schreuder, D.A. (1978). The use of yellow longitudinal markings on roads with two-directional traffic. R-78-38. SWOV, 1978.

- Schreuder, D.A. (1979). Public and vehicle lighting in residential areas. Paper CIBS Annual Conference, Harrogate, 19-23 May 1979. R-79-4. SWOV, 1979.

- Schreuder, D.A. (1980). Geprofileerde wegmarkeringen (Profiled road markings). R-80-51. SWOV, 1980.

- Schreuder, D.A. (1980a). The cost-effectiveness of vision tests for motorists. R-80-35. SWOV, 1980.

- Schreuder, D.A. (1981). De verlichting van tunnelingangen (The lighting of tunnel entrances). R-81-26 I+II. SWOV, 1981.
- Schreuder, D.A. (1981a). Visibility of road markings on wet road surfaces. Stichting Studiecentrum Wegenbouw SCW, Arnhem, 1981.
- Schreuder, D.A. (1982). Openbare verlichting en ongevallenkans (Public lighting and accident risk). Electrotechniek 60 (1982) 443-449.
- Schreuder, D.A. (1982a). De lichttechnische eigenschappen van lichtgekleurde wegoppervlakken (Lighttechnical proporties of light road surfaces). Wegen 56 (1982) 324-325.
- Schreuder, D.A. (1983). Principles of information transfer by road markings (Draft). In: CIE (1985).
- Schreuder, D.A. (1983a). The signalling functions of road markings. In: CIE (1983).
- Schreuder, D.A. (1984). Visibility aspects of road lighting. In: TRB (1984).
- Schreuder, D.A. (1984a). Visuele aspecten van wegmarkeringen. Verkeerskunde 35 (1984) 26-27.
- Schreuder, D.A. (1984b). Seitenreflektoren für Fahrräder. Licht 84, Mannheim, 1984
- Schreuder, D.A. (1985). De zichtbaarheid van wegmarkeringsmaterialen op natte wegen; Een aanvullende literatuurstudie (The visibility of road marking materials on wet roads; A supplementary literature review). R-85-23. SWOV, Leidschendam, 1985.
- Schreuder, D.A. (1985a). Visuele en verlichtingskundige aspecten van de verkeersveiligheid (Visual and lighting aspects of road safety). SWOV, Leidschendam, 1985. (In preparation).
- Schreuder, D.A. (1985b). Fundamentele overwegingen omtrent visuele en verlichtingskundige aspecten van de verkeersveiligheid (Fundamental considerations regarding visual and lighting aspects of road safety). R-85-61. SWOV, Leidschendam, 1985.
- Schreuder, D.A. (1985c). Toepassing en gebruiksmogelijkheden van retroreflecterende materialen in het wegverkeer (Application of retroreflecting materials in road traffic). R-85-62. SWOV, Leidschendam, 1985.
- Schreuder, D.A. (1985d). De theorie van de verkeersverlichting gezien vanuit de verkeerskunde (The theory of traffic lighting from the point of view of traffic engineering). Cursus "Weg- en Straatverlichting". PAO-VV, Delft, 1985.

- Schreuder, D.A. (1986). Verlichting en signalering van motorvoertuigen. (Lighting and signalling of motor vehicles) (Draft). SWOV, Leidschendam, 1986.

- Schreuder, D.A. & Oud, H.J.J. (1985). The design of tunnel entrance lighting. SWOV, Leidschendam, 1985. (In preparation).

- Schwab, K. (1985). Retroreflektierende Verkehrssicherheitseinrichtungen. Schriftenreihe Heft 4, p 1-35. Universität Innsbruck, 1985 (year estimated).

- Schwab, R.N. (1972). Minimizing the hazard of restricted visibility in fog. Public Roads 37 (1972) 53-56.

- SCW (1974). Wegverlichting en oppervlaktestruktuur (Road lighting and surface texture). Publicatie 34. SCW, Arnhem, 1974.

- SCW (1977). Asfaltdeklagen met gemodificeerde oppervlaktetextuur (Asphalt surfacings with modified texture). Mededeling 42. SCW, Arnhem, 1977.

- SCW (1977a). Internatioal symposium on porous asphalt. SCW Record 2. SCW, Arnhem, 1977.

- SCW (1982). Zichtbaarheid 's nachts van wegmarkeringen op droge en natte wegdekken (Night visibility of road markings on dry and wet road surfaces). SCW mededeling 52/SVT mededeling 17. SCW, Arnhem, 1982.

- SCW (1984). Lichtreflectie van wegdekken (Light reflection by road surfaces). Mededeling 53. SCW, Arnhem, 1984.

- Serres, A.M. (1975). La signalisation dans la conduite de nuit. Rev. Gén. des Routes Aerodr. (1975) no. 511, 39-54.

- Serres, A.M. (1978). Signalisation horizontale. Revue Gén. Routes Aérodr. 52 (1978) 538: 91-95.

- Serres, A.M. (1981). La visibilité des marques routières. Bull. Liason Lab. PC No. 114 p. 27-40, aug., 1981.

- Shannon, C.E. & Weaver, W. (1949). The mathematical theory of communication. The University of Illinois Press; Urbana, 1949.

- Spencer, D.E. (1960). Scattering function for fogs. Journ. Opt. Soc. Amer. 50 (1960) 584-585.

- Springer, J.F.; Huizinga, K.E. (1975). The road-picture as a touchstone for the threedimensional design of roads (two volumes). Rijkswaterstaat Communications No. 20. Government Publishing Office, The Hague, 1975.

- Stephenson, H.F. (1983). The photometry of retroreflective surfaces at large angles of incidence, such as road markings. In: CIE (1983).

- Stimson, W.A.; McGee, H.W.; Kittelson, W.K.; Ruddy, R.H. (1977). Field evaluation of selected delineation treatments on two-lane rural highways. FHWA-RD-77-118. A.M. Voorhees & Ass., Inc., McLean, Vir., 1977.

- Stoudt, M.D. & Vedam, K. (1978). Retroreflection from spherical glass beads in highway pavement markings. 1: Specular reflection. Applied Optics 17 (1978) 1855-1858.

- Stoudt, M.D. & Vedam, K. (1979). Retroreflection characteristics of spherical lenses, part. 3 (To be published) (year estimated).

- Sumner, R.L. & Shippey, J. (1975). The effect of rumble strips at the Dartford tunnel. Report 169 VC. TRRL, Crowthorne, 1975.

- SVT (1985). Voorrangsregeling - voorlopige aanbevelingen (Priority rules - preliminary recommendations). Mededeling: 30 SVT, Driebergen, 1985.

- SWOV (1969). Stads- en dimlichten binnen de bebouwde kom (Side lights and low-beam headlights in built-up areas). Rapport 1969-6/(Report 1969-7). SWOV, 1969.

- SWOV (1971). Symposium on psychological aspects of driver behaviour. Noordwijkerhout, The Netherlands, 2-6 August 1971. SWOV, 1971.

- SWOV (1973). Verkeersongevallen en wegdekstroefheden (Traffic accidents and skidding resistance). R-73-5 A+B. SWOV, 1973.

- Tenkink, E. (1985). Voorrang voor langzaam verkeer van rechts (Priority from the right for slow traffic). Werkgroep Veiligheid/R-85/2. Leiden, University, 1985.

- Tooke, W.R. & Hurst, D.R. (1975). Wet night visibility study. G. DOT Res. Proj. No. 6701. Dept. of Transportation of Georgia, 1975.

- TRB (1984). Providing visibility and visual guidance to the road user, Symposium, July 30 - August 1, 1984. Transportation Research Board, Washington, D.C., 1984.

- Triggs, T.J.; Wisdom, P.H. (1979). Effects of pavement delineation marking on vehicle lateral - position keeping. Human Factors Report HFR-10. Monash University, Clayton, Vic., 1979.

- Tromp, J.P.M. (1985). Splash and spray by lorries. R-85-5. SWOV, Leidschendam, 1985.

- Van Bommel, W.J.M. & De Boer, J.B. (1980). Road Lighting. Philips Technical Library. Kluwer. Deventer-Antwerpen, 1980.

- Van der Snoek, B. (1982). Poreuze wegen: beter zicht bij regen (Porous roads: better visibility in rain). Autokampioen 74 (1982) 594-597.

- Van Gorkum, F. (1982). De zichtbaarheid van zeven wegmarkeringsmaterialen onderzocht bij nacht en ontij. Wegen 56 (1982) 255-262.
- Van Gorkum, F. (1983). Untersuchung von Markierungsstoffen hinsichtlich ihrer Nacht-Nass Sichtbarkeit. Strassenverkehrstechnik 27 (1983) 78-83.
- Van Gorkum, F. (1984). Night-time visibility of seven road-marking materials. Traffic Engng. & Control 25 (1984) 176-184.
- Van Gorkum, F. (1984a). La visibilité de nuit de sept produits de marquage routiers. Rev. Gén. Routes Aérodr. (1984) 607: 7-14.
- Van Norren, D. (1981). Informatiedragers langs de weg. IZF 1981-C25. IZF-TNO, Soesterberg, 1981.
- Vedam, K. & Stoudt, M.D. (1978). Retroreflection from spherical glass beads in highway pavement markings 2: Diffuse reflection (A first approximation calculation). Applied Optics 17 (1978) 1859-1869.
- Visser, K. (1977). Markering met rammeleffect (Markings with rumble effect). Autokampioen (1977) 22 :1478-1479.
- Vlek, C. & Wagenaar, W.A. (1979). Judgement and decision under uncertainty. Chapter 6 Vol 2, p. 253-346. In: Michon et al. (eds.) (1979).
- Vos, J.J. & Padmos, P. (1979). The validity of interior light level recommendations: some neglected aspects. In: CIE (1980).
- VVAA (1986). Verkeersmedische dag (Traffic medicine day), Utrecht, March 1, 1986. VVAA, Utrecht, 1986.
- Waldram, J.M. (1938). The revealing power of street lighting installation. Trans. Illum. Engng. Soc. (London) 3 (1938) 173-196.
- Waldram, J.M. (1952). Street lighting. Edward Arnold & Co., London, 1952.
- Walker, J. (1986). Wonders with the retroreflector, a mirror that removes distortion from a light beam. Scientific American 254 (1986) No. 4 p. 112-117.
- Walraven, J. (1980). Visueel-critische elementen bij het nachtrijden; Een verkennend onderzoek (Visual critical elements for night driving; A pilot study). IZF 1980-C22. IZF-TNO, Soesterberg, 1980.
- Weir, D.H.; McRuer, D.T. (1967). Conceptualization of overtaking and passing manoeuvres on two-lane rural roads. Vol. IV, Driver control. Systems Technology Inc., Hawthorne, Cal., 1967.
- Welleman, A.G. (1977). Water op de weg. Publicatie L. SCW, Arnhem, 1977.
- Welleman, A.G. (1979). Ongevallen op nat wegdek II. Verkeerskunde 30 (1979) 552-555.

- Welleman, A.G. (1980). Aquaplanning, ongevallen op nat wegdek. Natuur en techniek 48 (1980) 98-117.

- Welleman, A.G. (1983). De veiligheid van fietsvoorzieningen (Safety provisons for bicycles). Verkeerskunde 34 (1983) 36-41.

- Welleman, A.G. (1986). Voorrang van rechts voor langzaam verkeer (Priority from the right for slow traffic). SWOV, Leidschendam, 1986. (In preparation).

- Wiener, N. (1948). Cybernetics. Wiley, New York, 1948.

- Wiener, N. (1954). The human use of human beings (2nd ed.). Doubleday, New York, 1954.

- Wilde, G.J.S. (1984). Evidence refuting the theory of risk homeostasis? A rejoinder to Frank P. McKenna. Ergonomics 27 (1984) 297-304.

- Wildervanck, C. (1981). Verhoogde wegmarkering en motorrijders. Nota ten behoeve van de SCW/SVT werkgroep E9. Verkeerscommissie KNMV, Ten Post, 1981.

- Wildervanck, C. (1982). Met de motor overweg. Verkeerstechnische Leergang 1982. ANWB, Den Haag 1982.

- Zijl, J.G.H. (1959). Visuele geleiding en misleiding door openbare verlichting (visual guidance and mis-guidance by public lighting). In: Anon (1959).

- Zwahlen, H.T. (1979). Driver eye scanning at tunnel approaches. Final Report, vol. 1. Project No. C4114. Franklin Institute, Philadelphia, Penn., 1979.

- Zwahlen, H.T. (1980). Driver eye scanning behaviour in rain and during an unexpected windshield wiper failure. Z.f. Verkehrssicherheit 26 (1980) 148-155.