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**LANE MARKINGS IN NIGHT DRIVING:
A REVIEW OF PAST RESEARCH
AND OF THE PRESENT SITUATION**

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November 1998

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16. Abstract <p>One of the basic driver tasks is to follow the road. In daytime driving, when the visibility of the road in clear weather is unobstructed, this is normally not a problem. However, when driving at night on dark roads with low beams, it is often quite difficult to see the direction the road is taking. Indeed, drivers state that poor road guidance is their main problem in night driving. To overcome this problem, roads are fitted with retroreflective pavement markings, which are visible in night driving.</p> <p>This study was conducted to review the role, effects, and functioning of lane marking in night driving. The report consists of five sections. Section 1 details the scope and the limitations of this report. Section 2 presents a discussion of drivers' needs for road guidance by means of pavement markers in general and lane markings in particular. Section 3 reviews the voluminous previous research on lane markings, focusing primarily on visibility and photometric characteristics of lane markings in night driving. Section 4 provides a summary of the issues related to lane markings. Section 5 presents the general conclusions and proposals for research topics and technical developments.</p> <p>The overall conclusion is that while drivers need both long-range guidance (a preview time of at least 5 s) and short-range guidance (a preview time of up to 3 s), present pavement markings often offer only short-range road guidance, especially in wet road conditions. Despite the extensive past research on pavement markings, many general and specific questions remain to be answered.</p>					
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EXECUTIVE SUMMARY

One of the basic driver tasks is to follow the road. In daytime driving, when the visibility of the road in clear weather is unobstructed, this is normally not a problem. However, when driving at night on dark roads with low beams, it is often quite difficult to see the direction the road is taking. Indeed, drivers state that poor road guidance is their main problem in night driving. This view is supported by accident statistics showing single vehicle accidents (running off the road) to be overrepresented in night traffic.

To overcome this problem roads are fitted with retroreflective pavement markings, which are visible in night driving. This study was designed to review the role, effects, and functioning of lane markings in night driving. Section 1 further details the scope and the limitations of this report.

Drivers' needs for road guidance should be the basis for the design of pavement markings. Consequently, in Section 2 the road guidance needs are analyzed based on existing driver models and on basic driver characteristics. It is concluded that drivers need road guidance and give this need very high priority. An effective lane marking provides a preview time of at least 5 s, which corresponds to about 140 m at a speed of 100 km/h. In daytime, both long-range guidance (at least 5 s of preview time) as well as short-range guidance (less than 3 s of preview time) are provided. Long-range guidance is generally carried out with central vision and it is performed only intermittently. Short-range guidance is carried out primarily unconsciously, continuously, and by peripheral vision. In night driving, however, drivers are often forced by poor visibility to forgo long-range visual guidance, and drive with the use of short-range guidance only. In such conditions, this sometimes has to be done with central vision, consciously, rather frequently, and presumably with considerable mental effort.

In Section 3, previous studies on pavement markings are reviewed. Specific attention is given to the measurement of the photometric properties of pavement markings because the photometric properties are critical for visibility. Studies of the general impact of lane markings on road accidents are reviewed. The conclusion is that good lane markings improve road safety. However, the effects are smaller than expected, except for combinations of marking systems (e.g., edgelines with centerlines and side-post delineators), which have substantial accident-reduction effects.

The presence and nature of lane markings affect drivers' choice of speed and lateral position. However, the results concerning speed changes are inconsistent. While some studies report a reduction, most report a slight increase in speed as a consequence of improved lane markings. A limited number of well-controlled subjective and objective visibility measurements of lane markings have been carried out. The results are summarized in tables showing that the visibility distances in night driving are normally considerably shorter than the safety criterion

chosen (140 m). The worst situation tested involved wet roads. The visibility distance of lane markings tends to be approximately proportional to the logarithm of the retroreflected luminance. The effects of other lane-marking characteristics (such as color and width) are also described.

The effects of various road, vehicle, and driver parameters are discussed. Concerning the road conditions, the main effects come from wear and weather. The effects of vehicle type and beam pattern on lane-marking visibility have not received much previous attention. There is evidence that older drivers and impaired drivers would benefit more from improved lane markings than would the average driver. Finally, durability, maintenance, cost, and photometric requirements and standards are briefly discussed.

Section 4 summarizes the main issues that have emerged from this review and presents suggestions for future research. In Section 5, the general conclusions are made, and proposals for research topics and technical developments are listed.

The overall conclusion is that while drivers need both long-range and short-range road guidance, present pavement markings often offer only short-range road guidance at night, especially in wet-road conditions.

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1. THE MAIN GOAL AND LIMITATIONS OF THIS STUDY

The main goal of this study is to review how driver needs for road guidance (to predict the course of the road, select the appropriate vehicle position on the road, and select adequate speed) are met. This report deals mostly with permanent, horizontal, lane markings (solid and dashed lines, and raised pavement markers) in reduced visibility conditions. Urban and illuminated areas are not covered, nor are temporary markings or roadway signs (except when interacting with permanent horizontal markings). The traffic control purposes and the symbolic aspects of the pavement markings are also not treated. Additionally, little attention is given to pavement markings under daylight conditions.

A summary of the major lane-marking issues will be provided. The main problems with present lane markings in night driving will be pointed out and recommendations for further research on lane marking will be made.

2. DRIVER NEEDS—THE PURPOSE OF LANE MARKINGS

The earliest reported use of painted line markings to divide traffic streams was in Michigan in 1911. In Wayne County, the commissioner initially painted white centerline markings in curves and bridges. He later extended their use to the entire highway. Prior to this, white stones had been placed in the center of the road, which at that time mainly consisted of gravel (OECD, 1975).

In traffic engineering terms the reason for having pavement markings are as follows:

- To guide the driver by indicating the course of the road and marking the road in relation to the surrounding areas.
- To warn the road users about special or hazardous events or locations related to the course of the road.
- To restrict the access to certain lanes (e.g., for special purposes only, car-pooling, or overtaking).
- To supplement and support information given by road signs and signals.

In this report we are mostly concerned with the first of these reasons, to guide the driver. The first question to be answered should then be: What needs do drivers have that can be helped by means of pavement markings to ensure accurate perception of the course of the road? The report will address lane markings in general and then focus on the more specific problems of lane markings in night driving.

In the search for relevant literature, three earlier general reviews have been located (OECD, 1975; Schreuder, 1986; and CIE, 1988). This report relies extensively on these reviews. However, so much has happened concerning pavement-marking research and technology during the last ten years that these reports are, to a large extent, not current with respect to more technical discussions of lane markings. COST, a European scientific cooperative within the transportation industries has been conducting a series of studies entitled, "Requirements for Pavement Markings." This project is planned for completion at the end of 1998, and the final reports on the various studies are not yet publicly available. However, a number of interim reports have been provided to us.

Driver needs for lane markings should be based on the tasks they perform and the effort required to carry out these tasks. Drivers consider the marking of road geometry and lane boundaries to be important elements that determine the difficulty of night driving (Walraven, 1980; and Padmos, 1985). Driver tasks traditionally associated with lane delineation and markings of roadway edge boundaries are lateral positioning, correct heading, and course changes (CIE, 1992). When lane markings fulfill driver needs, then they serve a purpose. If not, then they are little more than a legal measure intended to protect the authorities from liability.

This section addresses driver needs on the basis of driver models and specific driver characteristics. The first part reviews existing relevant driver models. The second part deals with other driver characteristics of possible relevance to the purpose and effect of lane markings. Finally, a number of conclusions about driver needs are stated.

2.1 Driver models

A useful driver model would make it possible to predict the behavioral effects of various changes in road, vehicle, and traffic parameters. However, no one model has reached general acceptance. The validity of existing models is often heavily contingent upon the purpose for which they were developed. Therefore any behavioral predictions based on existing driver models are risky. We would like to find a model suitable to describe the behavior of drivers, and in doing so better understand how lane marking can be used to aid the driver.

The oldest driver-performance model (Gibson and Crooks, 1938) has the distinction of being the only perceptually based model. It has an appealing simplicity because it integrates the vast number of driver tasks into two major tasks, instead of dividing the tasks into a large number of subtasks, as most models have done since then. The two major driver tasks according to Gibson and Crooks are:

- To create an area of safe driving in front of the vehicle.
- To decide upon a minimum stopping distance within this area of safe driving.

Lane markings, according to Gibson's concept of human orientation in space (Gibson, 1986), should support and enhance the visual flow over the retina, thereby facilitating perception of one's position, course, and speed along the road. During clear daylight the flow over the retina is rich. There are numerous stimuli extending for long distances in front of the vehicle that indicate the border of the road. Therefore, in clear daylight conditions, the effect of lane markings on driver orientation and guidance is of minor importance, as the information presented by lane markings is redundant with other visual stimuli. During daylight the lane markings are mainly perceived in peripheral vision and are used unconsciously (Blaauw and Riemersma, 1975).

According to Gibson (1986), the visual flow over the retina is what determines the driver's course and lateral position on the road. Riemersma (1985) showed that course selection is determined by the time derivative of the heading angle, and not by the heading angle or the lateral distance. According to Schreuder (1986), this means that the information needed to maintain course and lateral position must be collected centrally, not peripherally. We do not accept that conclusion. Rather, we support the Gibson theory that the driving course in daytime driving is decided mainly by the visual flow over the retina, which is accomplished by peripheral vision.

Riemersma (1985) carried out his studies of driver choice of course on a straight road. Curves represent a different situation. With curves, the main perceptual problem occurs before the curve where the driver has to predict the curvature and arch length of the curve (Schreuder, 1986). In daytime, lane markings add little to overcome this perceptual difficulty. When in the curve, the driver's way of deciding lateral position is very much the same as on straight roads. Eye fixation studies, however, indicate that, unlike straight segments of road where information acquisition is accomplished by peripheral visual processes, in curves drivers rely also on central visual processes (Nygaard, 1977).

On the other hand, in night driving, and in other poor visibility conditions, most of the distant and peripheral stimuli that would otherwise offer orientation are not visible. Additionally, the visibility of the

pavement markings are seriously reduced both ahead and in the periphery. In glare situations, pavement markings are sometimes the only stimuli the driver has available to guide the vehicle and allow lateral position to be maintained. As a result, drivers often fixate on the markings, and thus the markings are perceived in central vision and used consciously. Rockwell, Ernst, and Rulon (1970) showed that at night with oncoming vehicles, the center of drivers' fixation patterns move to the near right where the edgelines are.

Perhaps pavement markings fill the same purpose as handrails do in staircases. Handrails are often not used except when a person gets into trouble. Then the handrails offer excellent support. Some night traffic situations are difficult for many drivers. In such cases, available lane markings offer excellent support comparable to handrails in staircases.

In Gibson's terms, lane markings should influence drivers' ability to lay out the area of safe driving in front of the vehicle and influence driver perception of position on the road, and selections of the course and speed. For speed perception, dashed markings have advantages over solid markings because they are superior in providing additional speed cues.

In line with Gibson's thinking of ecological stimuli, some ideas from Gestalt psychology could be relevant. An important task of the lane markers is probably to create what the Gestalt psychologists call a good curve. A good curve does not have to be solid. Indeed, it might be based on a number of spots. However, the perceived gaps between the elements in the curve must not be too large.

Another driver model was developed by Michon (1971). Michon divided driving tasks into three levels: strategic, maneuvering, and control. This model was later modified by Janssen (1979) and it has become the most commonly used driver model. The three task levels were revised as follows:

- Strategic tasks (planning - conscious - minutes)
- Tactical tasks (maneuvering - sometimes conscious, sometimes unconscious - seconds)
- Operational tasks (handling - normally unconscious and automatic - milliseconds)

In terms of this model, lane markings should facilitate primarily the operational tasks, but should also influence the tactical tasks, especially when the lane markings contain symbolic information, such as a no-passing line. The transition from daylight to night also means that the task moves from operational to more conscious and tactical. The more the driver is required to centrally fixate on the lane markings, the more tactical the task is likely to be.

Rumar (1986) developed a task-oriented driver model along the lines indicated by Michon, but divided the tactical tasks into a number of separate activities. Another basic concept in Rumar's model is the self-paced character of the driving task. The difficulty of the driving task varies for many reasons (e.g., road, traffic, and vehicle conditions), and thus the demand on the driver is also continuously changing. The primary way a driver regulates this varying demand in a given situation is by choice of speed. If the situation becomes too difficult the driver can decrease speed. Likewise, if the situation is too simple the driver might increase speed to regulate the cognitive and perceptual demand. That is why the driving task, as defined by Rumar, is considered to be self-paced. Admittedly, there are other, less efficient, means for

drivers to control their mental load (e.g., by increasing headway or by choosing a position closer to the roadside).

The Rumar model has eight tasks:

- Planning the trip (mode, time, route, etc.). This task is mainly carried out before the trip.
- Navigating to find the planned route.
- Maintaining track along the road and avoiding stationary obstacles.
- Interacting with other road users without collision (overtaking, lane changing, etc.).
- Following the signed and unsigned rules and legislation (speed limits, stop signs, headway, lane position, etc.).
- Managing nondriving tasks (radio, climate, telephone, etc.).
- Handling the car (steering, braking, accelerating, etc.).
- Choosing a speed as a consequence of the demands from all these tasks.

In terms of this model, the lane markings should reduce the demand from the task to maintain track along the road. The demand from this task is likely not high in clear, daylight driving. However, at night and during reduced visibility, the mental load from this task will grow.

From this discussion follows another conclusion. If the lane markings are so effective that they considerably reduce the mental load and attention required to follow the road smoothly in night driving, drivers may react by increasing their speed. This type of behavioral adjustment shows up in many driving situations, and was one of the reasons behind the development of the risk homeostasis theory (Wilde, 1982).

Following a road can be characterized as a tracking task. This is consistent with a driver model presented by McRuer and Krendel (1959) which focused on the successive organization of perception. They distinguish between three levels of control (from low to high): compensatory behavior, pursuit behavior, and precognitive behavior.

Compensatory behavior is an attempt to reduce the errors between desired and actual vehicle motions, a pattern typically shown by the beginner driver. Drivers will carry out their tasks at a higher control level as they acquire skills. The higher processes require early information so that veridical predictions can be made. Thus, during clear daylight driving, experienced drivers follow the road by pursuit or precognitive behavior. At night, when visibility and road guidance is considerably reduced, however, they are often forced to regress to only compensatory behavior.

According to Good and Baxter (1985), it is logical to separate short-range delineation (used by drivers during night and in other reduced visibility conditions) from long-range delineation (used together with short-range guidance in good visibility conditions). The transition between short-range and long-range road guidance is not distinct, as it depends on a number of factors (e.g., speed).

Good and Baxter (1985) conducted studies based on the theory of McRuer and Krendel (1959). They found theoretical and empirical evidence for a fundamental difference between long-range and short-range road guidance. For example, painted white lines were found to be good for short-range guidance but not for long-range guidance, while post-mounted delineators were found to be good for long-range

guidance but not for short-range guidance. The concept of two separate road-guidance functions should be further studied.

2.2 Driver characteristics

For the purpose of this section, driver characteristics will refer to the characteristics of driver behavior that have not been emphasized in the comprehensive models discussed in the previous section. We will briefly discuss a few characteristics that are believed to be relevant for lane markings.

In common use, information is attributed to objects intended to convey a message (e.g., a road sign or a pavement marking). However, the formal definition of information is mainly related to the receiver and not to the source. It is a message that reduces uncertainty for the receiver. In other words, a particular pavement marking or road sign could contain information that is useful to one driver but not to another. For instance, a lane marking does not provide information to drivers who are clear about their position, but it is crucial information to drivers who are not sure about their position. A lane marking in itself is not necessarily information.

Common sense tells us that the road is important to drivers. There is reason to believe that the road is a priority element among the number of information sources that are available to drivers. Support for such an argument is found in the Gibson and Rumar models previously discussed. Experimental evidence was presented by Johansson and Backlund (1968) in their study of drivers' capacity to register information from road signs. They found that as driving conditions were successively degraded (e.g., snow, rain, fog, slippery road) the drivers missed more and more of the information that was less important to the immediate driving task of vehicle navigation. For example, first to disappear from driver perception were general warning signs, then speed limit signs, and then finally warning signs related to the road. Also, drivers were less likely to notice other road users when driving conditions were degraded. However, the perception of the road itself was always maintained.

Padmos (1985), Walraven (1980), and Walton (1975) studied what drivers considered to be critical elements in night driving. All three studies yielded essentially the same results. The elements that drivers considered to be most critical dealt with the course of the road and other geometrical road characteristics (e.g., lane and edge boundaries, curb delineation). Because the road is a priority stimulus for drivers, it should be enhanced by means of pavement markers to provide drivers with information that is considered important to them.

Feedback is very important for learning and developing skills, such as driving. Drivers should be informed whether their predictions and behaviors are correct or not. Pavement markings could improve the feedback to drivers concerning their predictions of the course of the road. Another important concept is feed forward. Drivers cannot just react to what is happening in their immediate vicinity. To do so would result in driving that is far from the smooth driving we try to achieve. Drivers have to predict what will happen in front or behind their vehicles and to behave or prepare their behavior on the basis of such

predictions. The richer the stimuli in front of them, the easier it is to make accurate predictions (Gibson, 1986).

Consequently, driver predictions are likely to be more accurate in clear daytime driving than they are in nighttime driving or in bad visibility conditions. In night traffic the available information sources are seriously reduced both in quantity and in quality, both ahead and along the sides. At night, adequate pavement markings should facilitate driver predictions of the course of the road ahead.

In clear daytime driving, experienced drivers tend to fixate several hundred meters in front of the vehicle, close to the point of infinity. It seems to be an unconscious attempt to reduce the probability of an unexpected event. In night driving, this fixation pattern has to change. There is nothing visible far away to fixate upon. Rockwell, Ernst, and Rulon (1970) showed that in night driving the fixation pattern moves much closer to the vehicle and slightly to the right hand side. This change is forced by the circumstances and is an illustration of the need for better pavement markings to accommodate drivers at night.

The farther away the route of the road can be recognized, the better are the predictions, thus resulting in easier driving. Again this should be no problem in clear daytime driving. At night, however, it poses many problems. Making lane markings visible from long distances in night traffic would facilitate driver predictions about the course of the road and thereby also facilitate the driving task.

According to Schmidt-Clausen and Damasky (1994), a majority of the pavement markings on two-lane roads appear between 7° to the left and to the right and about 1° down in the visual field. This is something that the light distribution of the headlamps should take into account. Pavement-marking visibility could be additionally enhanced by a vehicle lighting system that is better suited for that purpose.

It is more appropriate to discuss preview requirements in terms of time rather than distance, because the importance of time is more independent from vehicle speed. Weir and McRuer (1968) found that a preview time of 5 s offered a smooth and proper anticipatory steering behavior. In a later study Allen, O'Hanlon, and McRuer (1977) investigated the fixation points of drivers and found that they were 3 to 4 s ahead of the present position. Helmers (1978) suggests 4 to 10 s preview time for safe travel. Godthelp and Riemersma (1982) found that a minimum of 5 s of preview time is necessary for safe steering when the road is not straight. CIE (1988) suggests a 3 to 5 s preview time, but longer when approaching curves. CIE (1992) suggests a minimum of 5 s for long-range preview time. McGee, Moore, Knapp, and Sander (1978) found that drivers needed between 6 and 10 s to detect the necessity to change lanes and decide what course of action was appropriate.

In terms of driver brake reaction time, Johansson and Rumar (1971) found that in surprise situations a 2 s time is common. In modern traffic engineering literature a 1 s simple reaction time is often a standard.

These results suggest that a 2 s preview time is too short for road guidance, since it is adequate only for a simple braking reaction. We are not interested in just simple braking reaction time, because in road guidance there is uncertainty as to what the adequate response should be. Steering and avoidance maneuvers require decision time, and drivers need to identify what they see. A more realistic preview time

for long-range visual guidance appears to be 5 s, with 3 s as an absolute minimum preview time. At a speed of 100 km/h, 5 s would yield a preview distance of 140 m and 3 s would yield 84 m.

Andersson and Nilsson (1978) have shown that the risk of a single-vehicle accident (running off the road) in daytime is independent of the geometric standard of the road (expressed as average sight distance). However, in night driving, the single-vehicle accident risk increases proportionately with the decrease of average geometric sight distance. This is an indication of the importance of longer preview times.

Maximum visibility is the most important requirement of lane markings. However, there should also be a minimum distance at which the driver should be able to detect and identify pavement markings. We know that under poor visibility conditions (e.g., heavy fog) drivers use lane markers immediately in front of the vehicle for road guidance. Thus, it is also necessary for a driver to see pavement markings just in front of the vehicle. This may vary from a few meters to about 15 meters, depending on the design of the front of the vehicle and the driver eye position.

In Section 2.1 it was mentioned that tasks on the operational level, and sometimes tasks on the tactical level, are normally carried out automatically. Rumar (1990) proposed that the transition from automatic behavior to conscious behavior takes place when drivers' predictions prove to be incorrect. This has two important implications. First, one of the main tasks of driver attention and visual search must be to check whether the predictions made are indeed correct. Second, because prediction is more difficult during nighttime driving than during daytime, more of the operational and the tactical tasks are carried out consciously in nighttime traffic than in daytime traffic. In other words, lane markings are used differently in day and night driving. This reasoning is in accord with other arguments previously discussed.

The human visual system should not be compared to a passive photocell or camera. The visual system actively searches the visual scene for information to reduce the uncertainty of the driver. Motion in the visual field attracts attention, and the fixation of the eyes is automatically focused on that event or object. When drivers have difficulties predicting and following the course of the road, they actively search for pavement markings in the same way as somebody having problems in a staircase searches for the handrail.

An interesting approach to visual performance in night driving was presented by Leibowitz and his colleagues (Leibowitz and Owens, 1977; and Leibowitz, Owens and Post, 1982). According to the theory advanced by these studies, there are two main visual functions in driving. One is concerned with foveal vision and deals with detection and recognition problems of the driver. The other function deals with guidance and orientation, and is primarily carried out by peripheral vision. Owens and Andre (1996) indicated that the recognition function is impaired for all drivers in night traffic conditions. The guidance function, on the other hand, is less impaired at night for younger drivers than for older drivers (Owens and Tyrrell, in press). From this point of view, lane markings that could facilitate visual guidance in night driving should be more important for older drivers than for younger drivers.

Leibowitz and his colleagues (Leibowitz and Owens, 1977; and Leibowitz, Owens and Post, 1982) hypothesized that drivers are overconfident at night because they are unaware that their visual recognition

abilities are selectively degraded while their visual guidance is not. This theory questions whether improving visual guidance in night traffic is, indeed, helpful for improving safety.

Owens and Tyrrell (in press) and Rumar (1998) express analogous concerns. The self-pacing characteristics of driving mentioned by Rumar (1986) may be based on visual guidance, which is always present and provides good feedback. Drivers may overdrive their visibility distance for obstacles and other road users for which they have no or only limited feedback.

To address the hypothesis of visual guidance in night traffic being too efficient, it is important to consider the opinions and behaviors of drivers. A Swedish study (SNRA, 1996) showed that only a minority of drivers (30%) were satisfied with present lane markings. In a number of studies (Johansson and Backlund, 1968; Padmos 1985; Walraven, 1980; and Walton, 1975) it was shown that drivers believe that visual guidance is critical for night driving. Furthermore, drivers behave accordingly. In difficult situations, drivers disregard some information but always attended to the geometric road information. Only a small number of the respondents indicated that detection and recognition of other road users were critical problems in nighttime driving. What we do not know from these studies, however, is whether this opinion is a reflection of the frequency of or the amount of feedback from these targets, or a reflection of the critical need for visibility.

2.3 Conclusions

The conclusions from this section are as follows:

- The design and performance of lane markings should be based on driver needs for visual guidance.
- Driver models and knowledge about driver characteristics support the need for good visual guidance to reduce driver uncertainty, reduce the mental load, and facilitate driver predictions.
- Driving is a self-paced task and visual guidance plays a key role in this process.
- There is evidence for two fairly independent road-guidance functions. One is for long-range guidance (e.g., post-mounted delineators), and the other one for short-range guidance (e.g., painted edgelines).
- According to the driver models cited, during daytime experienced drivers obtain short-range visual guidance automatically and by means of peripheral vision.
- In clear daytime driving, lane markings contribute little to driver guidance.
- Road guidance at night is drastically worse than road guidance during the day. Rain and wet roads further increase the nighttime difficulties. Driving on wet roads at night is one of the more difficult and risky driving situations. Drivers are especially dependent on lane markings during such adverse and degraded conditions. Drivers consider road guidance to be their main difficulty in nighttime driving, and only a minority of drivers is satisfied with current lane markings.
- Drivers need about 5 s of preview time of the road ahead. An absolute minimum is 3 s.

- There are two widely separate views on enhancing road guidance. The traditional and established one states that more information about the road ahead results in smoother and safer driver behavior. Another view states that drivers' visual guidance is already better than drivers' recognition, and that visual guidance should not be further enhanced because that may lead to higher speeds and overconfidence.

3. REVIEW OF EXISTING STUDIES

This section reviews various studies that investigated lane markings. It is divided into twelve subsections, each covering a somewhat independent lane-marking issue. Emphasis has been placed on empirical measurements of the effects of lane markings. Additionally, standards and regulations for pavement-marking technology will also be addressed.

3.1 Pavement marking technology

The use of lane markings as a standard traffic engineering procedure started in Michigan in 1911. During the 1920s the practice spread across the U.S. and Europe. Typically, the color used for these markings was white. In Maryland it was noted in 1920 that the black bituminous joint sealer in the center of concrete roads unexpectedly functioned as a divider between the two streams of traffic (OECD, 1975).

Initially, there were no quality requirements on the paint used for markings. First requirements were suggested by Mattimore (1926). He was ahead of his time, and, to a great extent, the requirements today are similar to those he listed. Mattimore had day and night visibility and durability on his list, which are still the main requirements that need to be addressed (see Section 2.12).

Currently, pavement markings can be produced in various ways (CIE, 1988; and DELTA, 1997):

- *By application of paint.* The paint may be of a one- or two-component type. Paint may be applied either cold or hot, depending on the composition. The thickness of the paint applications typically ranges between 0.2 mm and 0.5 mm.
- *By application of plastic materials.* There are three basic types of plastic: hot-applied, thick plastics (thermoplastics), which are applied when heated to high temperatures; sprayed-on plastics, which are thinner thermoplastics; and cold-applied plastics. The thickness of the plastic markings are normally between 1 mm and 3 mm. Markings thicker than 3 mm should be avoided for several reasons (e.g., they may hinder water runoff).
- *By application of prefabricated lines.* These are fastened to the road surface with adhesives. (They are typically used for temporary markings.)
- *By installation of raised pavement markers.* These are made of metal or plastic material and equipped with directed retroreflectors, composed of glass beads or prismatic reflectors.
- *By installation of luminous raised pavement markers.* These fairly unusual markers are sometimes used on especially difficult sections of roadways. They are comparable to the raised retroreflective pavement markers except that they contain light sources and consequently work independently of any headlamp illumination.

In the case of paint, plastic materials, or prefabricated lines, the application is normally combined with the addition of glass beads. Glass beads are used either in the form of premixture, as drop on, or a combination of these methods. The glass beads are the active retroreflective material in pavement markings and make the markings appear bright in the illumination of vehicle headlamps. In order to enhance the

retroreflective performance of the markings in wet conditions, markings are designed with a textured surface by using large glass beads or other means to create vertical surfaces that protrude above the water surface. In order to increase the friction of pavement markings, the paint or plastic material is often used in combination with materials that enhance friction and offer added visual guidance.

Pavement markings are often referred to as horizontal signing and marking. However, profiled pavement markings and raised pavement markers are not really horizontal. They belong to an intermediate group of markings that are applied to the horizontal surface but have the active surfaces vertical.

Most pavement markings are white, but yellow markings are used in some countries (e.g., the U.S.). Other colors may be used in special cases (e.g., blue bicycle paths).

A small number of experiments have been carried out to develop fluorescent and luminescent pavement markers (e.g., Hopkins and Marshall, 1974; Lundkvist, 1993). Some produce promising results, others do not. These types of markings will not be further mentioned because they are still in the experimental stage, and only a few studies have been conducted.

A number of developments and studies have also been carried out on intelligent roadway-edge-detection systems. These devices detect when a vehicle is about to cross an edgeline and leave the road, and then inform the driver (passive systems) or take control of the vehicle (active systems). Special semi-intelligent, retroreflective, raised pavement markers were recently introduced by Astucia (1998). They are suitable for both temporary and permanent use, and can sense both moving objects (e.g., vehicles) and other conditions (e.g., ice). When triggered, they become luminous by means of light emitting diodes with various colors and flash rates.

3.2 Photometric measurements

The main factors influencing the visibility of pavement markings are their luminance, their luminance contrast with the road, and their size. To calculate the contrast we need to first measure the luminance of the road and of the markings. To obtain the luminance of the pavement markings, we need to use small angles that correspond to realistic traffic situations.

The photometric measurements should simulate a normal driving situation. Unfortunately, sometimes the symbols used for the various angles involved vary in different publications and different countries. A major difference is that the observation angle for pavement markings is defined differently in the U.S. and Europe (see Figure 1).

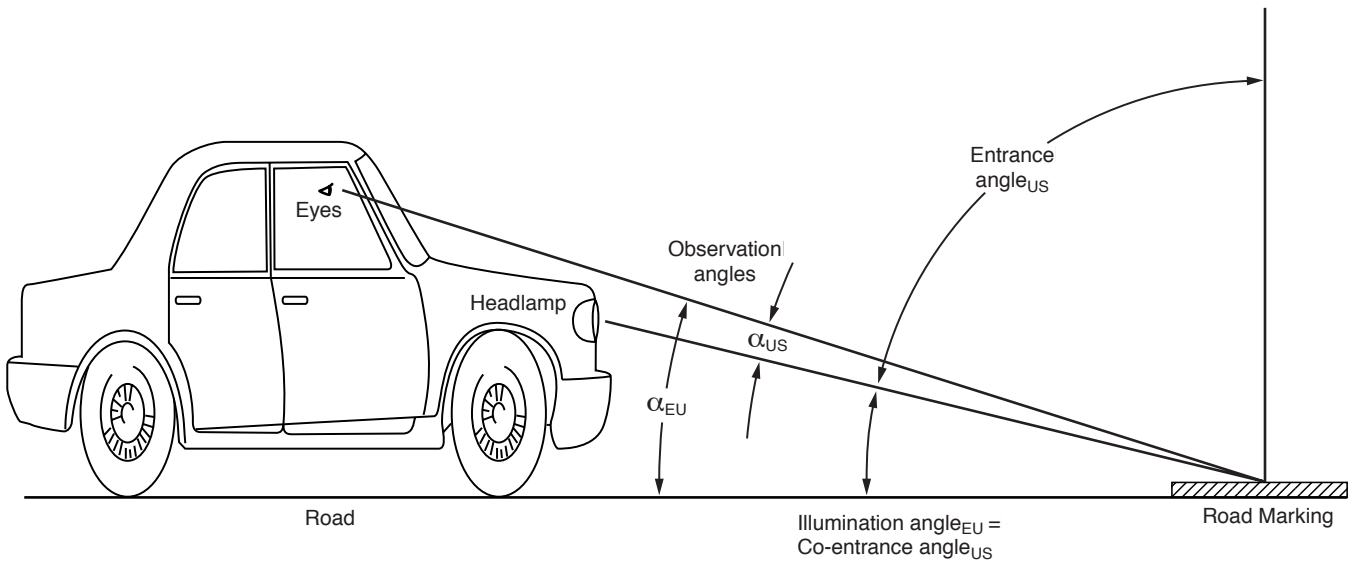


Figure 1. Main differences in the U.S. (US) and European (EU) nomenclature.

- In the U.S., the observation angle (α) is the angle between the illumination axis and the observation (measuring) axis.
- In Europe, the observation angle (α) is the angle between the observation (measuring) axis and the plane of the road marking.
- The illumination angle in Europe is the same as the co-entrance angle in the U.S. In other words, adding the U.S. observation angle to the U.S. co-entrance angle will yield the European observation angle. Conversely, subtracting the European illumination angle from the European observation angle will yield the U.S. observation angle.

In the text below, we will describe the angles used rather than provide only the symbols. We will use the U.S. definition of the observation angle, referring to it as α_{us} (versus α_{EU} for the European observation angle). We will use the European definition of the illumination angle (which corresponds to the U.S. co-entrance angle).

3.2.1 Measurement of retroreflective properties

The photometric quantity used for assessment of road surfaces in headlamp illumination is the coefficient of retroreflected luminance (R_l). It is defined as the quotient of the luminance of the surface in the direction of observation and the illuminance at the surface on a plane perpendicular to the incident light, and it is measured in $\text{cd}/\text{m}^2/\text{lux}$. On the other hand, for point sources (e.g., studs) the relevant photometric quantity is the coefficient of retroreflected intensity (R_I). It is defined as the quotient of the luminous intensity of the retroreflector in the direction of observation and the illuminance at the retroreflector on a plane perpendicular to the direction of incident light, and it is measured in cd/lux (CIE, 1988).

The measurement geometry has been studied and discussed in several publications (e.g., Lundkvist and Sorensen, 1980; Hoffmann and Firth, 1985; Attaway, 1989; CEN, 1992; Hedblom, Bradshaw, May, Jacobs, Szczech, Hodson, and Austin, 1993; and Shah, Nowakowski, and Green, 1998). The following angles have been found in various national and international proposals and standards (DELTA, 1990; and Hoffman and Firth, 1985):

- *Illumination (co-entrance) angle* (the angle between the illumination axis and the horizontal pavement marking): 4° (US), 3.5° (IRF, France, Italy, Spain, and Austria), 2° (Belgium, and Germany), 1.24° (Germany), and 0.74° (Denmark, and England).
- *Observation angle α_{us}* (the angle at the pavement marking between the observation axis and the and the illumination axis): 1.5° (USA, Austria, and Spain), 1.0° (IRF, France, and Italy), 1.3° (Germany), 1.05° (Germany), and 0.63° (Denmark, and England)

In comparison, given a headlamp mounting height of 0.62 m and a driver eye position of 1.11 m above the road (Sivak, Flannagan, Budnik, Flannagan, and Kojima, 1997), the actual illumination angles are 0.71° (at 50 m) and 0.36° (at 100 m), while the actual observation angles are 0.56° (at 50 m) and 0.28° at (100 m). Consequently, the angles in the above-listed proposals and standards are too large. However, there are two problems with reducing these angles. First, measurement at realistically small angles is difficult. Second, in real situations the road is never totally flat but has gentle undulation with a variety of amplitudes. At small angles such undulations result in large variations in the measurements.

Consequently, the goal has been to scale down the measuring situation by altering the apertures of light source and the photometers, and by using an instrument that is portable and easily operated by a single person and is capable of measuring photometric variables in both daytime and nighttime conditions. The problem with this approach is that the road cannot be scaled down.

The solution to these problems has been to increase the angles as far as possible without distorting the rank ordering between the results, in order to limit the large variation between the measurements for various road surfaces and pavement markings. Since the level of light to be measured is very low, it is important to control any stray light. It is also important to calibrate the instrument frequently because of its sensitivity to small changes in angles.

The European Standardization Committee (Comite European de Normalization, or CEN) has chosen as standard geometry for the luminance coefficient under diffuse illumination for the road (Q_d , measured in mcd/m²/lux) and for the coefficient of retroreflected luminance (R_L , measured in mcd/m²/lux) a situation corresponding to a distance of 30 m between a passenger car and the pavement marking. The eye height of the observer is 1.2 m and the height of the headlamps is 0.65 m. This yields an observation angle (α_{us}) of 1.05° and an illumination (co-entrance) angle of 1.24°.

Compact instruments intended for field measurements in practice are called retroreflectometers or just retrometers. There are presently a limited number of such instruments commercially available. They use different illumination angles (from 0.74° to 4.0°) and different observation angles (from 0.2° to 1.5°), and vary in other design respects (Hoffmann and Firth, 1985; Hedblom et al., 1993; and Shah,

Nowakowski, and Green, 1998). Thus, it is customary to calculate conversion factors for each retrometer in relation to a given standard geometry (see CEN, 1992).

Hoffmann and Firth (1985) report that the correlation between measurements carried out by means of Eriksen, Ecolux, Optronik, Wallometer, or Zehnter retrometers are all between 0.91 and 0.99. Lundkvist, Helmers, and Ytterbom (1980) compared the results from the Eriksen instrument with the results from Norwegian and Swedish experimental retrometers and concluded that it is difficult to compare results from one instrument with results from another because each have inherently differing characteristics. Hedblom et al. (1993) reached the same conclusion when they compared the subjective ranking of various marking products seen from different distances in a passenger car or a truck. The coefficient of retroreflected luminance as measured with standard retrometers did not relate to the brightness reported by the subjects. However, when the coefficient of retroreflected luminance in the real geometries was measured, the correlation between R_L and perceived brightness was high.

Unfortunately the results from retrometer measurements show considerable variability. The variability is especially large for the R_L , which is especially sensitive to small angles. Thus, a number of measurements should be taken on each marking. Another problem is that by sampling a small number of markers one does not know whether the samples are representative of the population. These issues are discussed in more detail by Lundkvist (1988a).

Furthermore, measurements may vary as a function of the time of year. Lundkvist (1990a) has found that the R_L winter values are reduced by half from their summer value. By spring the R_L values increase, although not to the same level as before winter. In Sweden, this effect is caused primarily by studded tires, but other factors also contribute to the decrease (e.g., cold climate and salting). Scheuer et al. (1997) studied the problem in Michigan and reported that the main factors affecting the decay of lane-marking retroreflectivity were snowplowing and sanding. The materials used and the type of pavement were not important factors. Dejaiffe (1987) discussed the possibility of using a retrometer equipped with a laser light source and a narrow-band filter to block out ambient light.

3.2.2 Field measurements of the coefficient of retroreflected luminance

The following is a sampling of studies dealing with the coefficient of retroreflection (R_L) of pavement markings:

- Rumar and Ost, 1974
- Serres, 1981
- Nordic Research Cooperation for Night Traffic, 1983
- Lundkvist and Nilsson, 1985
- Lundkvist, 1986
- Lundkvist, 1988a
- Lundkvist, 1988b
- King and Graham, 1989
- Lundkvist, 1990a
- Lundkvist, 1990b
- Obro, 1990
- Helmers and Lundkvist, 1991

- Hedblom et al., 1993
- Jacobs et al., 1995
- Jingryd, 1995
- Cotrell, 1996
- Scheuer, Maleck, and Lighthiezer, 1997
- DELTA, 1997
- Herland and Lundkvist, 1997

Several studies compared the performance of pavement markings with different compositions. Lundkvist (1986) varied the amount of beads, the size of the beads, the material composition of the beads, and the way the beads were applied (premixed or drop-on). The optimal percentage of premixed beads was determined to be 20%. If the premixed bead concentration is below 30%, there is no advantage to mixing small and large beads. For concentration of premixed beads above 50%, there is an advantage in reduced wear to mixing small and large beads. Plastic beads are durable, but possess poorer retroreflective performance. A mixture of glass and plastic beads may be optimal. In a later study (Lundkvist, 1988b) it was found that a mixture of 20% glass beads and 5% plastic beads was optimal for the markings of roads without street lighting. On roads with street lighting, the percentage of glass beads may be reduced to 10% to increase durability.

Jacobs, Hedblom, Bradshaw, Hodson, and Austin (1995) compared R_L as a function of distance (measuring geometry), compared visibility in static and dynamic conditions, related visibility to coefficient of retroreflected luminance, and compared visibility curves for various percentile performances. Hedblom et al. (1993) also studied the relationship between R_L and the measuring geometry by changing distance and type of vehicle. Their conclusion was that for modern retroreflective materials, measuring R_L with only one standard geometry does not provide valid results.

A series of studies from VTI in Sweden (Lundkvist, 1990b; Helmers and Lundkvist, 1991; and Jingryd, 1995) focused on wet road conditions. This was important because wet conditions pose one of the most visually difficult driving situations. It was found that the same measuring geometry could be used for dry and wet markings. Profiled markings were superior to flat markings, but the difference decreased slightly with increased wear.

Herland and Lundkvist (1997) studied a large number of various types (e.g., paint, sprayed plastic, thermoplastic, two-component plastic, and profiled thermoplastic) materials were installed on a stretch of road and measured regularly over a period of two years. The differences between the types were considerable. Paint markings were the first to suffer from heavy wear. Next was two-component plastics, and spray plastics. The materials that performed the best were the thermoplastics. All of the markings (except paint) met the minimum requirements ($R_L = 100 \text{ mcd/m}^2/\text{lux}$) after two years of heavy wear. The profiled markings suffered more than the flat markings, but were still more reflective in wet conditions. However, none of the profiled markings reached the requirement in wet conditions ($R_L = 25 \text{ mcd/m}^2/\text{lux}$) after one year. It should be noted that this study was made in Sweden where studded tires are common, so wear may be more severe there than in other countries.

Cottrell (1996) compared profiled (waffled) markings to markings with large beads under wet conditions and found that they both had disadvantages. He proposed to use raised pavement markers in combination with traditional markings if the primary need is to increase visibility at night in wet conditions.

DELTA (1997) refers to an unpublished study carried out in Sweden by VTI. This field study investigated the relationship between visibility and the coefficient of retroreflected luminance (R_L) in order to validate the DELTA model for calculation of pavement marking visibility. The independent variables included two levels of R_L (100 and 400 mcd/m²/lux), four different patterns of lane markers, and three different levels of headlamp illumination.

3.2.3 Raised pavement markers

ASTM D4280 (1996) and ASTM D4383 (1996) specify how the coefficient of luminous intensity (R_L , measured in mcd/lux) should be measured in laboratory conditions and provides minimum values for white, yellow, red, green, and blue. ASTM E1696 (1995) specifies how R_L should be measured with a portable retrometer in field conditions. The angles specified correspond to a passenger car at a distance of 300 meters or a truck at a distance of 150 meters. It is not known if there is any commercially available portable retrometer with these characteristics.

Liptak (1980) investigated the reliability of raised pavement markers (or “studs”). The study could not establish an effect of studs on accidents. One possibility for this is that the test stretches were too short. It was concluded that in moderate to heavy rain studs were the only road guidance system that remained optically functional. The damage to studs caused by snowplows was also studied.

Michaut and Bry (1985) concluded that in the worst condition (rain with oncoming glaring headlamps) a retroreflecting illuminance of 50 mcd/lux is necessary for the studs to be visible from a distance of 150 m. Increasing the retroreflecting illuminance to 100 mcd/lux only increased the visibility distance by another 20 m. The durability of raised pavement markers was also studied by McNees (1987) and Kidd (1990). These studies compared the durability of various types of studs and application methods. All markers in these studies lost 95% of their reflectivity within the first six months after installation. The main cause was believed to be improper installation.

Ullman (1994) studied the reflectivity of 17 types of studs both in the field and in the laboratory. A prototype portable retrometer had a measuring geometry of 4° illumination angle and 0.2° observation angle (Ullman and Rhodes, 1996). Field measurements were compared with laboratory measurements, resulting in a correlation coefficient of 0.93. The coefficients of luminous intensity of the 17 makes of studs, when new, ranged from 14 to 95 mcd/lux. Many studs lost much of their performance within one week due to dirt accumulation on the lenses. Later evaluations found that many of the lenses had been damaged by tires. Only a limited number of studs measured at least 50 mcd/lux (the minimum value) after 54 weeks. Studs with lenses covered by thin layers of glass yielded the highest readings.

3.3 General impact of lane markings on safety and other traffic goals

The two main crash categories that could be influenced by the lane markings are single-vehicle accidents and multivehicle head-on accidents. In both of these cases at least one driver has left his/her lane of travel. Angular collisions and collisions between cars and unprotected road users could also be influenced by the lane markings. In Europe and the U.S., single-vehicle accidents and head-on collisions account for approximately one-third of all accidents resulting in personal injury.

The Norwegian Handbook on Road Safety (TOI, 1997) provides a comprehensive summary of accident studies, with the results of each study weighted by its methodological quality. The results are shown in Table 1.

Table 1
Change in accident rates as a function of pavement marking procedure (from TOI, 1997).

Percent changes in number of accidents			
Seriousness of accident	Accident type	Best estimate	Range
Traditional edgeline (10 cm)			
Injury accidents	All types	- 3 %	- 7; +1
Property damage	All types	- 3 %	- 14; +10
Wide edgeline (20 cm) compared to 10 cm			
Injury accidents	All types	+ 5 %	-4; +14
Property damage	All accidents	- 1 %	- 16; +17
Profiled edgeline (rumble line)			
Injury accidents	All types	+ 2 %	-17; +26
Unspecified seriousness	Single-vehicle acc.	- 31 %	-45; -15
Centerline			
Injury accidents	All types	- 1 %	-8; +6
Property damage	All types	+ 1 %	-5; +6
Change from white to yellow centerline			
Unspecified seriousness	All accidents	- 6 %	-31; +29
Lane markings (same direction)			
Unspecified seriousness	All accidents	- 18 %	-51; +36
Raised pavement markers (studs)			
Injury accidents	All night accidents	- 8 %	-21; +1
Property damage	All night accidents	+ 3 %	-1; +7
Side-post delineators with retroreflector			
Injury accidents	All accidents	+ 4 %	-7; +16
Property damage	All accidents	+ 5 %	-2; +13
Combinations of edgelines and centerlines			
Injury accidents	All accidents	- 24 %	-35; -11
Combination of edgelines, centerline and side-post delineators			
Injury accidents	All accidents	- 45 %	-56; -32
Combination of edgelines and chevrons in curves			
Injury accidents	All accidents	- 19 %	-46; +23
Combination of studs and chevrons in curves			
Injury accidents	All accidents	- 6 %	-46; +63

TOI (1997) based the summary in Table 1 on the following studies:

Edgelines:

- Thomas, 1958
- Musick, 1960
- Willistone, 1960
- Basile, 1962
- Charnock and Chessell, 1978
- McBean, 1982
- Rosbach, 1984
- Willis, Scott, and Barnes, 1984

Profiled edgelines:

- Ligon, Carter, Joost, and Wolman, 1985
- Emerson and West, 1986
- Hickey, 1997

Wide edgelines:

- Hall, 1987
- Cottrell, 1988
- Lum and Hughes, 1990

Centerlines:

- Johns and Matthias, 1977
- Engel and Thomsen, 1983
- Glennon, 1985

Studs:

- Creasy, Ullman, and Dudek, 1989
- Griffin, 1990
- Wright, Zador, Park, and Karpf, 1982

Side-post delineators:

- Taylor and Foody, 1966
- Daas, 1978
- Johansson, 1986
- Kallberg, 1993

Several types of markings:

- Tamburri, Hammer, Glennon, and Lew, 1968
- Roth, 1970
- Bali, Potts, Fee, Taylor and Glennon, 1978
- Corben, Deery, Newstead, Mullan and Dyte, 1997

TOI (1997) did not include a limited number of other existing studies (e.g., Lassarre, 1976; Baumgartner, 1982; Hughes, McGee, Hussain, and Keegel, 1989; and Lundkvist, Ytterbom, Runersjo, and Nilsson, 1992). However, these studies produced results that were essentially similar to those in Table 1.

The first impression from Table 1 is that lane and pavement markings appear to have limited effects on safety. In many cases, the size of the safety effect is within plus or minus 5%, and many of the effects are not statistically significant. There are, however, some exceptions. Some markings seem to be very effective at reducing accidents.

Profiled edgelines seem to reduce single-vehicle accidents by about 30%. It is, however, difficult to tell how much of that effect is visual and how much is auditory or tactile. When tires roll on profiled edgelines the markers work as rumble strips, warning the driver that the vehicle is about to leave the lane. Neither is it possible to know to what degree weather conditions (wet or dry) influenced the effects.

Combinations of marking procedures appear more efficient than each single method individually. Edgelines combined with a centerline reduce the number of injury accidents by almost 25%. Edgelines combined with a centerline and side-post delineators significantly reduce the number of injury accidents by about 45%. One way to explain these results may be to refer to Good and Baxter (1985). Earlier it was suggested that drivers use two distinct, but complementary, road guidance functions, long-range and short-range guidance. Side-post delineators may provide long-range guidance, and the painted lane markers may support short-range guidance.

Only a few studies have focused on the nighttime effects of pavement markings. Based on the earlier discussion, it could be expected that the effects of pavement markings on safety are stronger at night than during the day. But the findings from the available limited number of studies are not consistent.

No good studies of the safety effects of pavement markings in reduced visibility conditions other than darkness (e.g., fog) have been found. Another issue that does not receive much research attention relates to the influence of weather on the safety effects of lane-marking systems. It is likely that under adverse weather conditions, profiled systems, such as raised pavement markers and profiled rumble lines, would be superior to traditional painted markings.

A similar issue relates to special roadway situations, such as curves. While the overall impact of lane markings might be limited, there may be specific situations (e.g., on curves) where the impact might be substantial. However, the existing studies do not provide information on roadway-specific benefits of different types of systems.

In several studies many variables are varied simultaneously, thus making it difficult to determine the specific effect of each variable. For instance, in one study the lane markings on a number of roads were altered, while other roads that have not been modified served as controls. However, the modifications were made simultaneously in such a way that the lane width was increased, the edgeline was made three times as wide, and the edgeline was changed from a dashed line to a solid line. In other words, three variables changed simultaneously, and it is impossible to determine the effects of each individual variable. Furthermore, many of the studies have not adequately controlled for possible confounding factors, such as the statistical effect of regression to the mean or the behavioral compensation effect. The regression to the

mean problem, which yields effects of a treatment that are artificially large, could be controlled by certain statistical measures. Driver compensatory behavior reduces the safety effect of a treatment, and thus requires control of the possible compensatory behavior.

Several British and U.S. studies have controlled speed before and after the introduction of pavement marking measures (Thomas, 1958; Williston, 1960; Stimson, McGee, Kittelson, and Ruddy, 1977; Mullooney, 1982; Willis, Scott, and Barnes, 1984; and Cottrell, 1988). The results indicate that when pavement markings are introduced, speed increases by about 10%. However, after frequent travelers of the roadway get accustomed to the new markings, the speed tends to go down again, although rarely back to the original level.

The increase in speed as a consequence of improved pavement markings indicates that the potential compensation effects discussed earlier are real, but not as strong as feared. For side-post delineators such compensation effects are stronger. In fact, on roads with relatively low geometrical standards, introduction of retroreflective side-post delineators appears to have a negative effect on safety as a result of the considerable increase in speed (Kallberg, 1993). This is difficult to accept for those who experience the improved visual guidance and the positive reactions from drivers.

Measuring driving speeds before and after an introduction or modification of lane markings may also indicate changes in traffic flow and a higher level of mobility.

Pavement markings have limited impact on the environment. Rumble lines (profiled markings) and studs may cause additional noise. This is, however, their very purpose, and the only individuals for whom this may be disturbing are those living along the road. The only air pollution effects of pavement markings are those that may relate to road workers (e.g., from liquid paint solvents, plastic or color particles, or pigments).

3.4 Behavioral effects of lane markings

It is always difficult to measure safety effects using accident analyses. One reason is that accidents are, fortunately, rare events. Therefore, they are sensitive to random variation if investigating only limited areas or time periods. In other words, the reliability of accident effects is limited. Therefore another approach has been tried. Instead of measuring accidents directly, efforts are made to find behavioral measures that correlate with accidents. Driver behavior is always present and can be readily measured. However, the validity of such indirect safety measures is limited. In other words, one must choose between high validity and limited reliability (direct safety measures, such as accidents) and limited validity and high reliability (indirect behavioral measures, such as speed).

The behavioral effects of lane markings that could be strongly related to safety are few. The primary variable used is driver speed. As discussed above, driving is a self-paced task and when the task to follow the road becomes easier the speed will increase. However, is this self-pacing based on road geometry, road standard, or visibility? The relation between speed and safety under normal driving conditions is well established (Nilsson, 1984). Several studies (and real life accidents) show that drivers'

choice of lower speeds when conditions worsen (e.g., in fog) is, usually, an incomplete regression towards a condition of constant safety (Harms, 1992). That is to say, speed is not reduced as much as it should be if safety is to be kept constant.

Drivers often undercompensate in a degraded situation. Another question is whether drivers overcompensate (increase their speed too much) in an improved situation (e.g., with highly effective road guidance) so that safety is ultimately decreased. This potential effect was discussed in Section 2 and in Section 3.3.

Another behavioral performance indicator is lateral position and variability on the road. These variables are easy to measure (high reliability) but their relation to safety is not as clear as that for speed (low validity). Correlations between 0.7 and 0.8 for vehicle position or position variability and accidents have been obtained (Stimson, McGee, Kittelson, and Ruddy, 1977). A combination of speed and position would likely provide the most comprehensive indicator of driver performance.

Another behavioral performance indicator is the number of overtakings. If lane markings reduce the number of overtakings, safety should improve. However, there are no studies on the relationship between this variable and accidents, and therefore its validity is unknown.

Finally, driver opinions concerning lane markings should not be overlooked as a possible indirect measure of safety. However, the relationship between this subjective evaluation and accidents is not known. It can be assumed though, that subjective evaluation is highly correlated with driver behavior. When a marking is perceived as good then there is a high probability that behavior is influenced. Subjective evaluation is also a measure of comfort.

Visibility is a common variable in subjective evaluation studies. It is unknown whether there is a difference between subjective evaluation of lane marker visibility and general evaluation of how “good” a lane marking is. It is likely that these two subjective measures are highly correlated, and that they measure, to a great extent, the same thing.

3.4.1 Driver behavior changes on straight sections of road

Table 2 summarizes the findings concerning behavioral changes on straight sections of road. Table 2 is based on the following studies:

- Taragin, 1958
- Thomas and Taylor, 1960
- Hubbell and Taylor, 1968
- Cottrell, 1985
- Lundkvist, Ytterbom, and Runersjo, 1990
- Lundkvist, Helmers, Nilsson, Ytterbom, Runersjo, and Lauridsen, 1990
- Lundkvist, Ytterbom, Runersjo, and Nilsson, 1992
- Carlsson and Lundkvist, 1992

Table 2

Summary of results from studies of lateral vehicle edge-to-edge clearance between oncoming passenger cars at night as a function of edge delineation. In all studies there was a centerline.

No line	10 cm dashed white	10 cm dashed yellow	5 cm solid white	10 cm solid white	10 cm solid yellow	20 cm solid white
0.5 – 1.7 m	4.3 –7.4 m	3.7 – 7.0 m	3.4 m	2.6 – 4.6 m	3.6 – 7.0 m	2.1 m

A certain degree of caution is warranted when comparing and interpreting the effects of the treatments listed in Table 2. Due to the measuring and metric conversions some error may be introduced, and differences inherent in the studies (e.g., lane width, traffic volume, and roadway complexity) may influence the results. The ranges given represent the lowest and highest averages from each study. If only one number is given, there was only one relevant study. Overall, it is evident that pavement markings influence driver behavior when measured by lateral position.

For the no-edgeline control it is consistently found that drivers tend to position their vehicles close to the centerline. One reason for this behavior is that drivers tend to stay closer to the line on the side of the steering wheel. This was observed when Sweden changed from left-hand to right-hand traffic. Another reason may be that without clear demarcation of the edge, the driver is uncertain about the roadway width and where the pavement ends. Therefore, there is a tendency to drive closer to the centerline because it is a clearly defined reference line. Such behavior, while reducing the chances of roadway excursions, results in a higher probability of head-on collisions.

While the exact effect for the edgeline delineation practices is unclear, the general results are that dashed lines tend to yield greater separation between oncoming vehicles (that is, drivers position their vehicles closer to the edgeline). It may be that a solid line is more imposing and causes drivers to shy away from the edge (as supported by the evidence from the widest (20 cm) conditions). However, additional research is needed before any recommendations could be made concerning desirable delineation practices because the differences between the treatments were small, and because line type provides additional symbolic information which may counteract lane-position measures.

Lundkvist, Ytterbom, and Runersjo (1990) evaluated driver behavior before and after a new edgeline marking procedure was implemented in Sweden. Edgeline delineation of roadways 9 m wide had previously been marked with 10-cm-wide dashed lines; this was compared against a novel treatment using a 20-cm-wide solid line placed closer to the roadway edge. After implementation it was determined that drivers laterally positioned their vehicle farther from the centerline, resulting in greater lateral distances between oncoming traffic. This treatment also yielded more variability in the lateral position, which was seen as a favorable outcome in order to minimize the formation of longitudinal ruts. Additionally, speeds were reduced after implementation of the new edgeline treatment.

In later studies driver behavior was monitored before and after edgeline treatments for roads that were 13 m wide (Lundkvist, Helmers, Nilsson, Ytterbom, Runersjo, and Lauridsen, 1990; Lundkvist, Ytterbom, Runersjo, and Nilsson, 1992; and Carlsson and Lundkvist, 1992). Edgeline delineations had previously been 10-cm-wide dashed lines placed 2.6 m from the road's edge; this was tested against a new treatment of 30-cm-wide solid lines placed 1.0 m from the road's edge. As had been found for roads that were 9 m wide, the new edgeline treatment resulted in greater lateral separation between oncoming vehicles, and the lateral position was more variable. Contrary to the previous findings, however, there was no change in speeds.

The general conclusion from these studies is that wider solid edgelines that are closer to the road's edge (thereby increasing lane width) result in greater lateral separation between vehicles with a potential for reducing accident frequency and severity.

3.4.2 Driver behavioral changes in curves

Shinar, Rockwell, and Malecki (1980) studied the effect of edgelines on speeds in curves. Speeds were found to be the slowest for the no-edgeline control. The increased speeds with edgeline delineation were considered positive by the authors because the speeds were still slower than during the daytime, and because the increase in speed to closer mimic daytime behavior was an "indication of increased confidence by drivers in their judgment."

Agent and Creasey (1986) evaluated the use of raised pavement markings, transverse lines, rumble strips, side-post delineators, and chevrons on slowing vehicle speeds in curves. Also tested was a treatment involving a visual illusion. Specifically by using post delineators where the reflector is placed at an increasing height, the perceived sharpness of the curve is increased. In general, the treatments had no effects on speeds, but there were effects on lane positions consistent with a reduction in the number and severity of lane encroachments. The use of chevron signs significantly reduced the approach speeds to curves.

Zador, Stein, Wright, and Hall (1987) found that when chevrons were used, drivers tended to navigate closer to the edge, while when post delineators were used, drivers drove closer to the centerline; in both conditions speed increased. There were no differences between the two treatments, and thus either could be used effectively to warn drivers of an approaching curve. Consistent with the conclusion of Shinar et al. (1980), Zador et al. (1987) suggested that the increase in speed with delineation was a consequence of drivers having more information and a better understanding of their environment.

Zwahlen (1993) evaluated multiple configurations of delineation treatments including chevrons, arrow signs, side-post delineators, guardrail reflectors, and object reflectors on vehicle approach and curve-center speeds. Since no significant change-of-speed results could be found among the treatments, Zwahlen concluded that all treatments performed equally well in alerting drivers to the presence of a curve. A no-delineation control was not used.

A recent study by Retting and Farmer (1998) evaluated the use of pavement markers and found a 7% decrease in vehicle speeds. The authors were encouraged that this was an indication that delineation would result in slower curve speeds, yet commented that more control than they could attain was desired in future studies.

3.4.3 Conclusions

The results on the effects of lane delineation on speeds (whether on straight roadways or on curves), while inconsistent, tend to suggest that delineation may slightly increase speeds. The changes in speeds, along with the lateral-position data imply that delineation enhances the visual information concerning the future path of the road. While a better understanding of the roadway environment generally advances safety, future studies should evaluate the long-term effect of treatments, and the potential consequences of the possible overconfidence. Relevant to this is the finding of Zwahlen and Schnell (1997b) that longitudinal eye-fixation distance increased when higher-visibility pavement markings were used. In other words, as the richness of the information about the roadway ahead increased, drivers tended to fixate farther down the road.

3.5 Visibility of lane markings

The main factors influencing the visibility of traditional (painted) pavement markings are the luminance contrast with the road, their luminance, and their size. For retroreflective markers, as well as luminous, raised pavement markers (which may be treated as point sources), the main factor for their visibility is the illuminance reaching the observer. The threshold depends on the surrounding luminance.

A number of studies have been carried out to establish visibility requirements and detection distances for various types of pavement markings under varying conditions. In the discussion below, we will differentiate between studies employing subjective versus objective techniques to measure visibility differences, and between field versus laboratory or theoretical studies.

3.5.1 Subjective Evaluations

Past studies on the visibility of pavement markings have predominantly involved subjective field evaluations. Early tests were often performed by a single traffic engineer who compared pavement marking products that were, typically, transverse lines across the roadway surface. Such evaluations consisted of viewing the markings (without control for observation angle) to determine subjectively which lines “seemed brightest.”

Later studies attempted to improve upon this technique by soliciting the responses of impartial volunteers. The observations were made sometimes directly in a field setting, but more often involved

viewing photographs of test sites. Regrettably, even the field studies were often undertaken without adequate controls for such factors as angles of observation. On the other hand, the studies utilizing photographs, while more controlled, were plagued with the inadequacy of photographic equipment, which was incapable of accurately representing the retroreflective materials as the human eye would see them.

Despite these general problems, several well-controlled studies have been performed. A brief review of the notable articles is provided. A tabular summary was not attempted because making direct comparisons between studies that used different subjective scales and stimulus presentation techniques would be difficult and potentially misleading.

Ritter (1973) varied bead size gradations, flotation coatings, refractive indices, and quantities (kg/l) to evaluate wet and dry nighttime visibility of beaded painted lines. Double yellow lines were painted along a test stretch of rural road; the left line was always a standard application reference line, and the right line was a test stripe of varying experimental specifications. Subjective ratings supported the use of the standard reference line. Croteau (1977) found that uniform gradation floating beads, applied at a standard flow rate of 0.5 kg/l, were to be recommended.

McNees (1987) addressed the wear effects on visibility of pavement marking. Chronological photos were taken of a test site that had suffered a loss of beads over time. The results indicate that pavement markings became semi-effective as guidance aids when only 75% of the beads remained, and ineffective when only 50% of the beads remained. McNees recommended painting maintenance when bead concentrations fall below 75%.

Ethen and Woltman (1986) used beads of various refractive indices and concentrations to manipulate reflectance in order to determine a suggested minimum reflectance standard. The results indicate a replacement value of 100 mcd/m²/lux, based on a rating of “minimally acceptable” at a viewing distance of 58 m.

Graham and King (1991) evaluated pavement-marking reflectance to determine a minimum recommended level. The viewing distance was 30 m. Based on the results, Graham and King recommended a minimum reflectance level of 93 mcd/m²/lux for safe nighttime travel.

Jingryd (1995) evaluated the subjective visibility of flat and profiled markings both in daylight and at night. Jingryd obtained a rank correlation of 0.81 between Q_d and subjective visibility in daylight, and a rank correlation of 0.61 between R_L and subjective night visibility. A weak, but significant, positive relation was found between R_L readings in dry and wet conditions. Profiled markings were significantly better than flat markings, but the difference became smaller the more the markings were subject to wear.

3.5.2 Objective visibility measurements

While subjective evaluations are generally made at suprathreshold levels, visibility or detection measurements are made at thresholds. Visibility studies determine a maximum distance that observers manage to achieve under full attention and controlled conditions. Zwahlen (1989) showed that when reflective targets appear in the periphery of the eye, the reflectivity of the target needs to be increased in order to ensure timely recognition. Zwahlen found that at a peripheral angle of 10° the detection distance of a target is approximately half of the corresponding foveal (central) detection distance.

However, should pavement markings be treated as peripheral or central targets? One way to approach this question is using the concept of conspicuity. Conspicuity refers to the attention value of an object, its capacity to be noticed in the visual field. There are however, two types of conspicuity, one concerning unexpected targets (e.g., vehicles) and another one concerning expected targets (e.g., pavement markings). The latter one needs considerably lower contrast and luminance to be detected (Jenkins and Cole, 1986). According to this point of view, we need not treat pavement markings as peripheral targets.

Section 1 concluded that about 5 s would be suitable as minimum preview although shorter times (3 to 4 s) could reluctantly be accepted. Considering speeds of about 100 km/h, 5 s preview would result in a preferred minimum detection distance of 140 m, and a 3 s preview time would result in an absolute minimum visibility distance of 84 m. We will now turn our attention to literature that evaluates how well present lane-marking systems meet these criteria. The reviewed studies include the following:

Field studies, daytime

- Forsberg, Dahlstedt, and Laurell, 1977

Field studies, nighttime

- Rowan, 1963
- Dierks and Runhage, 1983
- Michaut and Bry, 1985
- Helmers and Lundkvist, 1991
- Jacobs, Hedblom, Bradshaw, Hodson, and Austin, 1995
- Zwahlen and Schnell, 1995
- Zwahlen, Hagiwara, and Schnell, 1995
- Zwahlen, Schnell, and Hagiwara, 1995
- Zwahlen and Schnell, 1996
- Zwahlen and Schnell, 1997a,b

Field studies day and night

- Rumar and Ost, 1974

Laboratory and theoretical studies, nighttime

- Blaauw and Padmos, 1982
- Gorkum, 1982

Theoretical and field studies, nighttime

- Zwahlen, Miller, Khan, and Dunn, 1988
- Obro, 1990
- Schnell and Zwahlen, 1996
- DELTA, 1997

Daytime. We found two relevant studies. In neither of them were the illumination level and the retroreflected luminance well controlled. In one of them (Rumar and Ost, 1974) the effect of wear and dirt level on dry and wet road surfaces was used as the dependent variables. Night retroreflectance was used as criterion of performance also in daylight. This is inappropriate because the fewer active pearls in a marking the brighter the marking looks in daylight. Therefore, their data for degraded markings in daylight were not included in the summaries.

Forsberg, Dahlstedt, and Laurell (1977) studied the impact of road brightness and sun angle as the dependent variables. Specifically, this study measured luminance levels of road surfaces and of lane markings. The measurements were made at an angle of 5.7°, which does not correspond to any of the presently used or proposed angles. However, for brightness measurements in diffuse illumination this angle should not be critical. Using the luminance readings, contrasts between lane marking and road surface were calculated. Table 3 summarizes the visibility distances obtained by Rumar and Ost (1974) and Forsberg et al. (1977).

In Table 3, as well as in Tables 4 through 7, the variability listed is the range between the means obtained in the different studies. All studies that were included have carried out measurement of visibility in an acceptable way. Therefore all studies enter the tables with the same weight although the studies used different numbers of observations. What differs between the studies is the control of the independent variables, such as level of illumination, luminance factor of the road, and coefficient of retroreflection.

The reviewed studies are for many reasons not completely comparable, and they have not studied exactly the same conditions. Therefore not all studies are included in all cells for a given summary table (Tables 3 through 7). Consequently the cells are not always comparable. However, they still provide a representative level of visibility for each condition, which is the primary goal here.

Table 3
Daytime visibility of painted, plastic, and prefabricated lane markings (center and edgelines).
The data are from field studies, and they are for new and dry markings.

Ambient light or sun behind observer	100 - 300 m
Sun facing the observer	55 - 140 m

The influence of the sun angle proved to be substantial. The contrasts between the markings and the road varied between 0.9 (road surface brighter) to 22.3 as a function of the sun angle. The color and

brightness of the pavement markings is very important for contrast and visibility in ambient illumination or when the sun is behind the observer. When the sun is facing the observer, other factors, such as texture, are more important for contrast and visibility.

From a safety point of view, the maximum visibility levels in Table 3 are acceptable, while the lower levels of visibility are not. This finding is of some concern, because the markings were new and their visibility would degrade further with age and wear. However, lane markings are probably not as important in daytime traffic as in nighttime traffic. In daytime, there are other stimuli offering long- and short-range guidance information.

High beams. The visibility of lane markings under high-beam illumination has been the subject of several studies. Rumar and Ost (1974) primarily examined the effects of wear and dirt on the performance of lane markings in wet and dry conditions. However, the obtained light measurements are insufficient for a detailed analysis. Helmers and Lundkvist (1991) varied headlighting by changing the aiming angle of low-beam headlamps. Retroreflective coefficient (R_L) was varied by changing the percentage of glass beads in the markings. The effect of dry and damp conditions on marking visibility was also investigated. DELTA (1997) refers to another study by VTI in Sweden that evaluated two levels of retroreflective power ($R_L = 100$ and 400 mcd/m²/lux), three levels of vehicle illumination, line type (dashed or solid) and lane width (10 cm and 30 cm). Table 4 summarizes the results.

Table 4
Nighttime visibility (m) of painted and thermoplastic lane markings (center and edgelines) illuminated by vehicle high-beam headlamps under varying conditions as measured in field studies.

Condition of pavement markings	New		Old	
	Dry	Wet	Dry	Wet
Detection distance	55 - 172m	40 - 90m	30 - 136m	28 - 36m

When compared against the criteria discussed in Section 2 (84 to 140 m), only the high-end values for new, dry pavement markings meet the preferred minimum visibility level (140 m). Furthermore, the data in Table 4 are based on average values. Consequently, a substantial number of individual visibility distances were substantially shorter than the visibility levels presented here.

Low beams. Most visibility studies are performed for low beams, with or without oncoming (glaring) low beams. Nine studies have been found dealing with various aspects of lane-marking visibility in low-beam headlamps. The first well-controlled study was made by Rowan (1963). Of interest in this study was visibility in dry and wet conditions, with and without glaring lights. However, the markings were significantly different in size and form from normal lane markings, and therefore the data from this study are not used in the summary below. Dierks and Runhage (1983) studied detection distance as a function of the coefficient of retroreflection on dry and wet surfaces in three experiments. Michaut and Bry (1985)

investigated raised pavement markers and post-mounted retroreflective delineators. Zwahlen, Miller, Khan, and Dunn (1988) performed both theoretical and field studies of optimal distance between side-post delineators. Rumar and Ost (1974) and Helmers and Lundquist (1991) have already been discussed briefly above.

Zwahlen and his collaborators (Zwahlen and Schnell, 1995; Zwahlen and Schnell, 1996; Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen, Schnell, and Hagiwara, 1995; and Zwahlen and Schnell, 1997a,b) have carried out a large number of field studies. Of interest in these studies were variables such as retroreflectance, line color (white versus yellow), centerlines versus edgelines, narrow versus wide lines, dashed versus solid lines, single solid lines versus double solid lines, distance between double solid lines, detection of beginning versus end of a line, and, a detection of a curved line. A model was also developed for calculation of detection distances to lane markings (Zwahlen and Schnell, 1996). Obro (1990) and DELTA (1997) also developed models for calculation of visibility distances. An attempt was also made to validate these models against field measurements of visibility performed by VTI in Sweden. Jacobs, Hedblom, Bradshaw, Hudson, and Austin (1995) compared the visibility of six pavement-marking products that differed primarily in retroreflective properties. Table 5 summarizes the visibility results of these field studies.

Table 5
Nighttime visibility of painted and thermoplastic centerline and edgeline markings under low-beam illumination.

Condition of markings	New		Old	
	Dry	Wet	Dry	Wet
No oncoming glare	50 – 87 m	34 – 38 m	30 – 65 m	27 – 33 m
Oncoming low-beam glare	50 – 77 m	40 – 50 m	30 – 40 m	30 – 40 m

Although the data across the cells are not completely comparable, they still serve to demonstrate the inadequacy of the visibility distances provided. None of the average visibility distances met the minimum acceptable distance of 140 m.

Two types of markings are not included in Table 5—profiled pavement markings and raised pavement markers—because no suitable field studies have been identified. An exception is a study by Michaut and Bry (1985) on raised pavement markers, but it was only available in a summary version. Michaut and Bry concluded that a coefficient of luminous intensity of 50 mcd/lux is required to reach a minimum visibility of 150 m. Doubling the coefficient of luminous intensity (to 100 mcd/lux) increased visibility only to 170 m.

While there is a lack of visibility studies concerned with profiled pavement markings and raised pavement markers, there are studies that measured luminance under various conditions. We will return to these later.

The following paragraph provides a summary of findings concerning the color, configuration, and wear sensitivity. This summary is based primarily on the research by Zwahlen and his collaborators, and is elaborated in more depth in Sections 3.6 and 3.7.

The visibility of the end of a line is 10 - 50% longer than the visibility of the beginning of the line. Edgelines are detected earlier than centerlines, but the differences are small and statistically not significant. Results for the effect of color are not consistent. Solid double lines are detected at distances significantly farther than dashed lines. Because the visibility under ideal conditions is frequently only marginal, obliteration of markings could be critical. No significant differences were found between detection distances for a 10 cm and a 20 cm line width, except in curves. DELTA (1997) described an unpublished Swedish study that claimed a significant difference in detection distance between lines 10 cm wide and lines 30 cm wide. Rumar and Ost (1974) found that one-week accumulation of dirt reduced the visibility of lane marking by 60% on high beams and 30% on low beams. However, these data are from Sweden where studded tires are used extensively, resulting in high levels of dirt.

3.5.3 Theoretical and laboratory studies, and models

Theoretical studies are often based on photometric measurements of pavement markings or on laboratory studies addressing the contrast sensitivity of the human eye (Blackwell, 1946; and Adrian, 1989). The model of Blaauw and Padmos (1982) is the most general of these visibility models. Zwahlen, Miller, Khan, and Dunn (1988) addressed post-mounted delineators, while Schnell and Zwahlen (1996) began to develop a visibility model for pavement markings. Obro (1990) describes an early Danish attempt to formulate a visibility model for pavement markings. DELTA (1997) includes a more mature Danish visibility model that includes field validations.

Two theoretical studies present results that make it possible to compare field measurements with theoretically calculated predictions. Those studies are Blaauw and Padmos (1982) and DELTA (1997). The Blaauw and Padmos study is the more comprehensive of the two. It addressed visibility distances for new and old markings under both wet and dry conditions. The findings of Blaauw and Padmos are summarized in Table 6.

Table 6
Comparisons between empirical and calculated visibility distances for painted and thermoplastic lane markings under low-beam illumination without oncoming vehicles.

Condition of markings	New		Old	
	Dry	Wet	Dry	Wet
Field Studies	50 – 87 m	34 – 38 m	30 – 65 m	27 – 33 m
Calculated Visibility	40 – 75 m	70 – 80 m	60 – 95 m	20 – 70 m

Calculated visibility distances are generally longer and have wider ranges than real-life detection distances. (One pattern in Table 6 is somewhat puzzling: The calculated lower range of visibility for new, wet markings is longer than for new, dry markings.) Later models (Schnell and Zwahlen, 1996; and DELTA, 1997) produce predictions that are more consistent with empirical data.

We have not found any extensive studies of visibility of either profiled pavement markings or raised pavement markers (studs). Therefore the calculated visibility distances for these two types of lane markings (as presented by Blaauw and Padmos (1982)) are listed in Table 7.

Table 7
Calculated nighttime visibility (m) for profiled pavement markings and raised pavement markers (studs) by low-beam headlamps under varying conditions.

Condition of markings	New		Old	
Condition of the road	Dry	Wet	Dry	Wet
Profiled pavement markings	110 – 120 m	90 – 100 m	80 – 90 m	75 – 80 m
Raised pavement markers	150 – 250 m	110 – 200 m	75 – 125 m	80 – 135 m

The data in Table 7 should be handled with care, however. Both of these types of lane markings appear to be superior to traditional markings, especially on wet roads. However, whether profiled lane markings are superior for short-range road guidance in daylight has not been determined.

Raised pavement markers exhibit superior visibility over other types of markings, especially in rainy and wet conditions. An interesting effect observed in empirical studies is that wet conditions increase the photometric performance of some raised pavement markers. Whether this is related to a self-cleaning process, more light reflected towards the markers in wet conditions, or both, is unknown. One reason why studs are not used frequently in parts of the world where snow is common is that it is hard to design them in such a way that they can withstand damage from snow plows. Recessed (snowplowable) markers have been specially designed for use in areas where damage would otherwise result to typical raised pavement markers.

The differences between empirical visibility measurements and calculated visibility have been mentioned previously. Both are necessary because practical considerations (e.g., expense and time) sometimes prevent field measurements. Thus, it is vital to know the relationship between real world visibility and photometric performance so that visibility can be predicted with acceptable precision.

Field measurements of visibility do not always correspond to true values in real traffic where drivers are not equally prepared and focused, and where their headlamps are not well maintained. The true values are certainly shorter. Roper and Howard (1938) calculated an attention factor of two to transform experimental visibility distances to real traffic visibility. That is to say, in real traffic situations detection distances are often only half as long as those distances obtained in experimental situations.

3.5.4 Relationship between photometric values and visibility

Photometric measurements are taken as a substitute for visibility measurements for various reasons. They are simple and inexpensive to carry out. However, in order for them to be meaningful, it is necessary to know their relationship to visibility. In this section we will compare subjective and objective visibility data with corresponding photometric values. The goal is to determine whether it is possible to recommend specific photometric values for minimum safe visibility.

Interest has been focused on the variability of the photometric measurements. This variability reflects the reliability of photometry. Unfortunately, few studies have been conducted on the relation between physical and behavioral results. Such a relationship would indicate the degree of validity of photometric measurements.

Blackwell (1946) reported a series of studies on visibility as a function of object size, ambient luminance, and contrast. Results from this report have been used to calculate the visibility of pavement markings (Allen, O'Hanlon, and McRuer, 1977; and Blauuw and Padmos, 1982). However, such calculations need to be validated.

Subjective visibility

Croteau (1977), unfortunately, used a relatively crude method to measure photometric properties, and therefore his data were not used here.

Serres (1981) related the coefficient of retroreflected luminance (R_L) to the evaluation obtained from a number of subjects whose task was to say whether the brightness was acceptable or not. The R_L values varied from 70 to 300 mcd/m²/lux. The report concludes that the minimum coefficient of retroreflected luminance for replacement of the markings should be 100 mcd/m²/lux, and that a value below 150 mcd/m²/lux is not acceptable to the average observer. Both values seem low. Requirements are always a compromise between what is needed and what is technically possible. It is pointless to write requirements that no marking can reach. Today new technologies make it possible to reach higher values than previously obtainable.

Ethen and Woltman (1986) used the same measuring geometry (Ecolux) as Serres to study subjective visibility in seven steps under ideal conditions. They mention the need to simulate more real conditions such as oncoming glare, curves, rain, misaimed headlamps, and impaired drivers, which are normal in real traffic. The R_L values varied between 20 and 1,100 mcd/m²/lux. They summarized their results by reporting the relationship between subjective visibility and the coefficient of retroreflected luminance for dark roads with low beams, and dark roads with low beams and street lighting in terms of two regression equations. Both indicated that visibility is related to the log-value of R_L , with a correlation of 0.93. Ethen and Woltman (1986) concur with Serres' recommendation of 100 mcd/m²/lux for replacement of markings. However, they argue that the acceptable R_L value for new materials should be higher: at least 400 mcd/m²/lux on dark roads, and at least 300 mcd/m²/lux on lighted roads.

Graham and King (1991) used pavement markings with R_L values between 17 and 371 mcd/m²/lux. Young subjects rated the visibility in three steps (less than adequate, adequate, and more than adequate). They concluded that 100 mcd/m²/lux was an adequate performance. They suggest, however, that under more realistic conditions higher values are needed. Consistent with the findings of Ethen and Woltman (1986), visibility was found to be related to the log value of R_L , with a correlation of 0.89.

Hedblom et al. (1993) studied suprathreshold visibility. They found that measuring R_L by using standard geometries did not correlate well with subjective evaluations. However, when they modified the photometric measurements to better agree with the actual situation, the correlation improved greatly.

Jingryd (1995) found that the correlation between subjective visibility in daylight and the respective Q_d was 0.81, while between subjective night visibility and the respective R_L was 0.61.

Objective visibility

Rumar and Ost (1974) obtained visibility distances of 250 m in daylight, 110 m using high beam, and 50 m using low beams. (This study, however, did not fully control all relevant photometric variables.) Dierks and Runhage (1983) conducted three well-controlled experiments on a real road or a closed track. The level of retroreflection (as measured by an Eriksen retrometer) was varied by changing the bead concentration. The main conclusion was that visibility was related to the log value of R_L , with a correlation coefficient of 0.89.

In a pilot study, Helmers and Lundkvist (1991) also varied the R_L values by changing the bead concentration in the markings. Both dry and wet road conditions were used, under both low- and high-beam illumination. The relationships between the coefficient of retroreflected luminance R_L (as measured by an LTM 800 retrometer) and visibility distance to the pavement marking in a variety of conditions were reasonably well described by log functions (with correlation coefficients between 0.73 and 0.85).

The above studies are consistent in finding that visibility is related to the log of the coefficient of retroreflected luminance. However, what also needs to be established is the relationship between photometric (or visibility) performance and safety. Lee, Maleck, and Taylor (1998) attempted to address that issue. Pavement markings in four areas of Michigan were monitored for retroreflective performance. Parallel to this, data on night accidents relevant to pavement markings were also collected. No correlation was found between the retroreflection measurement (as measured by a Mirolux-12 retrometer) and accident rates. However, all markings passed the Michigan minimum retroreflectivity level for repainting (100 mcd/m²/lux) during the duration of the study, possibly accounting for the lack of correlation.

The one referenced study on raised pavement markers (Michaut and Bry, 1985) provides two points only. A coefficient of luminous intensity of 50 mcd/lux yielded a visibility distance of 150 m, and a coefficient of luminous intensity of 100 mcd/lux yielded 170 m. That indicates that the visibility of studs could also be related to the logarithm of the retroreflected performance.

Jacobs et al. (1995) studied a number of pavement-marking products, which varied in their level of retroreflectance. Their R_L values ranged from 70 to 300 mcd/m²/lux. Detection distances were measured under both static and dynamic conditions. However, no regression equations between visibility and the log

R_L were calculated. The dynamic detection distances were considerably lower than the static ones (by 30 to 40%). Finally, their data were compared against the data from Zwahlen (1997). The comparison indicated a high degree of correspondence in the relationship between visibility and R_L in each study.

Sorensen (1998) developed a visibility model for pavement markings based on a number of basic variables, such as luminance and size of the marking, veiling luminance, and the age of driver. On the basis of these variables, he calculated a “visibility level.” A comparison was made between the results of calculations with this model with the visibility distances obtained in an empirical study. This comparison demonstrated that the model worked quite well.

Schnell and Zwahlen (1996) have developed a computer model for estimating pavement visibility. The model, CARVE (Computer Aided Road-marking Visibility Evaluator), has been calibrated and validated in a number of studies. In the latest study (Zwahlen and Schnell, 1998), driver age was investigated in order to include that variable in the CARVE model. Age proved important because the visibility level of the older drivers (average age 68 years) was 45% less than the visibility levels obtained for the younger group (average age 23 years).

3.5.5 Conclusions

To conclude, the visibility offered by present lane markings at night is too short from a safety point of view. Indeed, visibility would need to be doubled in dry conditions and tripled in wet conditions to reach minimum levels considered “safe.”

Visibility of traditional pavement markings is related to the log of the coefficient of retroreflected luminance (R_L) expressed in $\text{mcd/m}^2/\text{lux}$ and measured with the standard measuring geometry. Higher correlations are achieved when the pavement markings are measured using real traffic geometry.

3.6 Design characteristics of lane markings

Design characteristics refer to properties of the lane markings that do not directly relate to their retroreflective characteristics. The main characteristics are color of pavement marking, line width, solid versus dashed lines, length of line/length of gap ratio for dashed lines, and single versus double lines. These characteristics have been touched upon several times in the preceding sections. Here we will only summarize the main findings, and add what has not been discussed earlier.

3.6.1 Color of pavement markings

Basic human factors principles indicate that color coding is a useful means of conveying information (see, for example, Sivik, 1975; Christ, 1975). It is also possible that color can make a target more conspicuous (Mehta, Vingrys, and Badcock, 1994; and Isler, Kirk, Bradford, and Parker, 1997). The benefits of color have been incorporated into signing and pavement-marking standards to aid in the discrimination and the identification of their intended message. The largest portion of literature addressing color deals with signing, which is outside of the scope of this report. Thus, only general issues concerning color will be discussed, along with the studies on the use of white versus yellow for lines and reflectors.

The main difficulty with the use of color use lies in the light-filtering process needed to produce colors. As light strikes a colored object, some component wavelengths are absorbed, all except those that characterize the perceptual “color” of the object. In the case of white, all wavelengths are returned; while in the case of black, no wavelengths are returned. This process involves a reduction in the intensity of the light returning to the observer for any object that is not white.

Recent articles have looked at the specific advantage of color when light intensity is held constant (see Venable and Hale, 1996; Schumann, Sivak, Flannagan, Traube, Hashimoto, and Kojima, 1996; and Sayer, Mefford, Flannagan, Sivak, Traube, and Kojima, 1998). These studies have shown considerable psychological effects of color. However, when typical products are used, Marsh and Tyrrell (1998) found that the effect of color was negligible. This was attributed to the sizeable disparity in retroreflective power inherent in the materials based on the filtering process due to color as discussed above. What this suggests is that a critical element in visibility of a material is the intensity of light that the material is able to return.

In 1972 the National Joint Committee on Uniform Traffic Control Devices established the policy that edgelines within the U.S. should be marked with white markings, while centerlines separating opposing traffic should be marked in yellow. Roth (1974) found that when the median side of the curve was marked with yellow markings and the right edge was marked with white markings drivers exhibited less centerline-straddling behavior. That is, drivers maintained a more consistent track within the safe boundaries of their lane. Furthermore, fewer lane changes were observed with this marking pattern. It was suggested that this was because the ability to distinguish the median and right edges of the road had been enhanced (prior practice was to mark both sides with white, possibly making one side indistinguishable from the other).

Since edgeline standardization established a system in which the color of an edgeline would need to be identified if the driver were to receive full benefit of the environmental information, Jacobs and Johnson (1995) addressed whether at night yellow lines were discernible from white lines. This research was in response to the observation that under low illumination certain yellow marking products that exhibited yellow daytime color failed to exhibit yellow nighttime color. Subjects viewed yellow materials against fresh, black asphalt. Results indicated that the nearer the target was, the more yellow it appeared, and that those materials that had a higher color saturation were reported to have a more yellow appearance.

Zwahlen, Hagiwara, and Schnell (1995) studied the visibility of yellow pavement markings when certain percentages of their reflective material had been removed, thus reducing the total reflective surface area. This approach to reducing luminance was taken because a reliable method for introducing consistent material wear could not be found. Results indicated that the original centerline marking treatments provided barely adequate visibility performance, and could thus only sustain a loss of 5 to 10% before the visibility performance of the system fell below acceptable levels.

Zwahlen and Schnell (1995) studied the effect of line width and color (white and yellow). Although they did not aim to compare the effect of color, it is possible to do so from their data since the effect of the line widths they studied was very small. From their data it could be concluded that the detection distances for the yellow lines are approximately 20% shorter. Based on the general color discussion above concerning the real-world relationship between color and the intensity of light, this finding is not surprising. Yellow provides less retroreflected light than white under otherwise constant conditions. Thus, one would expect it to have a shorter visibility distance.

Zwahlen and Schnell (1996) asked subjects to indicate end detection (when the lane marking stops). High-retroreflectivity white yielded the farthest detection, followed by high-retroreflectivity yellow and medium-retroreflectivity white, which performed equally well. Both yellow and white low-retroreflectivity materials resulted in the shortest detection distances. No statistically significant effect for color was found in this study, so no change in the existing policy of yellow median edgelines and white right edgelines were recommended. There was, however, a large, significant effect for retroreflectivity. It was noted that even the most visible material, high-retroreflectivity white, would allow only a 2.5 s preview time (when traveling at 90km/h). To lengthen detection distance and enhance safety, a recommendation was therefore made to explore materials that produce higher retroreflectivity values.

3.6.2 Line width

In general, line width has an effect on driver behavior. Specifically, the lateral distance from the edge of the road tends to be positively correlated with line width. In other words, as the width of the edgeline increases, so does the distance from that line. However, an apparent discrepancy in the literature was seen in the series of studies done by Lundkvist and his colleagues in Sweden (Lundkvist, Ytterbom, and Runersjo, 1990; Lundkvist, Helmers, Nilsson, Ytterbom, and Runersjo, 1990; Lundkvist, Ytterbom, Runersjo, and Nilsson, 1992; and Carlsson and Lundkvist, 1992). In these studies new line patterns that were both wider and solid (versus dashed) were tested, and it was found that drivers positioned themselves farther from the centerline. While, superficially, this is contrary to the findings of existing literature, it must be acknowledged that the lane and shoulder widths were also changed simultaneously. Because the lanes were much wider in the experimental condition, it could very well be that the vehicle positioning change was more a function of the lane width than the line width or style.

Line width should have an effect on lane-marking visibility, because a wider line contains more retroreflective material and should therefore provide more light to the driver. In a series of studies, Zwahlen and colleagues (Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1995; Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1997a) varied the width of the lines from 5 cm to 20 cm. The results showed a tendency for longer visibility distances with increasing line widths, and in most of the studies the differences were statistically significant. DELTA (1997) described an unpublished Swedish study that showed a statistically significant difference in detection distances between 10-cm wide lines and 30-cm-wide lines. Overall, the wider lines were detected approximately 30% sooner than the narrower lines.

3.6.3 Solid versus dashed lines

As indicated in Table 2, vehicle lateral edge-to-edge separations were found to be closer when edgelines were solid as opposed to dashed. It may be that a solid line is more imposing and thus it causes drivers to shy away from it. However, as indicated earlier, these differences were small and any improved vehicle positioning performance may be negated by symbolic information that is provided by line type. This is a subject for further study.

In a series of studies, Zwahlen and his colleagues (Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1995; Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1997a) studied detection distances for solid and dashed lines. They concluded that solid lines are detected significantly earlier than dashed lines. The differences ranged from 10 to 50%, with wider lines increasing the differences.

3.6.4 Line length and line gap configuration

The question of line length and line gap configuration in pavement markings is one that is at the very heart of the decision-making process concerning pavement markings: What is the least expensive alternative that still conveys vital guidance information to the drivers? The shorter the lines and the larger the gaps, the less expensive the material is. However, to be effective and worth the cost of installation, the marking pattern must still serve its fundamental purpose: to be detectable and safely guide the driver.

Oliver (1977) tested a new configuration of 3-m lines with 9.1-m gaps against the standard at that time of 4.6-m lines with 7.6-m gaps. No significant difference was found. Therefore, it was recommended to implement the new configuration in an effort to minimize the cost.

Dudek, Huchingson, and Woods (1980) conducted an extensive investigation of ten line-to-gap configurations, with line lengths ranging from 0.3 to 2.4 m and gap lengths ranging from 5.5 m to 14.6 m. There were no significant differences in speed among the ten conditions studied. However, there were significant differences in vehicle positioning. Patterns with short line lengths separated by extensive gaps were associated with missed curves and wide lateral position deviations from the centerline during daytime tests. Furthermore, subjects rated these short line-to-long gap ratios as difficult to track. At night, no

significant performance differences were found, but subjects rated the 2.4 m/9.8 m configuration the best, and the 0.6 m/11.6 m configuration as the worst.

Dudek, Huchingson, Creasey, and Pendleton (1988) studied the effects of lane-marking configurations on driver behavior in work zones. Areas were marked with the following line/gap configurations: 0.3 m/11.9 m, 0.6 m/11.6 m, and 1.2 m/11.0 m. Performance and ratings indicated that all configurations performed equally well under the test conditions (relatively flat, two-lane, two-way, high-speed roadways), but the authors cautioned against generalization to roadway conditions not represented in the study.

Harkey, Mera, and Byington (1993) compared driver performance in work zones when marked with three types of line/gap configurations: 0.6 m/11.6 m, 1.2 m/11.0 m, and 3.0 m/9.1 m. Significant differences were found in driver performance. Specifically, drivers drove faster and positioned their vehicles closer to the centerline in the 3.0 m/9.1 m condition than in either of the other two conditions. Additionally, lateral position variability (consistency of track) and the number of lane encroachments both decreased as line length increased. The differences were magnified during periods of adverse weather (rain, wet roads).

The visibility of line/gap configurations of 3.0 m/9.1 m and 1.2 m/11.0 m have been studied by Zwahlen and his colleagues (Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1995; Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1997a). As expected, there was a clear tendency for farther visibility distances for the lines with longer lines and more narrow gaps. However, the overall differences failed to reach statistical significance. It was concluded that increasing the amount of pavement marking material by means of increasing the line length and decreasing the gaps does not pay off proportionally in increased visibility. (It should be pointed out, however, that when the visibility is too short there may be a payoff anyway.)

3.6.5 Single versus double lines

The data from Zwahlen and his colleagues (Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1995; Zwahlen, Hagiwara, and Schnell, 1995; Zwahlen and Schnell, 1997a) indicate that the main factor that influences visibility is the amount of retroreflective material. Whether this is accomplished with one wide line or two narrow lines was not important. No effect was found for the lateral separation distance between double lines.

3.6.6 Conclusions

Color has been used sparingly as a method to distinguish pavement markings (much less than in traffic signs). In the U.S., yellow separates lanes of opposing traffic, while white separates lanes with same direction of travel and marks the roadway edge. However, using color reduces the amount of light reflected to the driver and thus the visibility of the marker. With recent advances in retroreflection technology it may

soon be the case that inexpensive materials with high retroreflective power are available in a wide array of colors. At that time, research should investigate the potential for use in the roadway environment given the advantages of symbolic coding and conspicuity. Until then, however, color use should remain limited.

Edgeline width has been shown to influence drivers' lateral positioning. As the width increases, drivers track on a course that is farther from the edge of the road (closer to the centerline). This may be of use to traffic engineers. For example, in areas where there are hazards along the road (e.g., ditches, rocky terrain, bridges, curves, etc.), or narrow or no shoulders, it may be advantageous to use wider edgelines that have greater visibility and thus minimize the chances of dangerous roadway excursions. In areas where there is a smaller danger should a vehicle momentarily leave the road, narrower edgelines could be used to maximize lateral separation of oncoming vehicles and thereby minimize chances of head-on collisions.

Standard edgeline delineation practices in the U.S. and many European nations involve the use of solid lines. The goal of edgeline marking is to delineate the roadway and enhance driver knowledge of the environment. It follows that as drivers' knowledge of the roadway increases, roadway excursions and accidents decrease. To that end, solid edgeline markings have an advantage over dashed lines because they are more visible, and they tend to move drivers farther away from the edge.

The results on the effects of line-to-gap ratio for dashed lines are not consistent. In general, those that find an effect, be it driver performance or rating, indicate that longer lines are preferable over shorter lines. If an error is to be made, it is better to side with caution. To that end, ratios consisting of short lines with long gaps should be avoided pending evidence to the contrary.

Finally, the question of the superiority of single or double lines seems largely unresolved. The issue, stripped of the value of symbolic coding, seems more fundamentally linked with the visibility of the materials. This can usually be summed up with the phrase, "there is never too much of a good thing." That is, the greater the visibility the better the marker will delineate the roadway and guide the driver.

3.7 Road and weather conditions

There are several road and weather conditions that influence the visibility of lane markings. They include wear, dirt, rain, fog, frost, and snow. Except in the case of rain and wet pavement markings, very few studies exist that evaluate the influence of these conditions on pavement-marking effectiveness.

3.7.1 Wear and dirt

Wear removes parts of the markings, particularly the retroreflective parts (e.g., the beads). Wear is especially severe in areas where there is snowfall. Damage resulting from the use of snowplows and tire studs or chains forces these areas to replace or repair the markings every spring in order to return the materials back to their effective condition. Damage caused by plows and traction aids may be reduced with the implementation of recessed pavement markers or durable, high-quality, raised markers (see, for example, Epstein, Grieser, Preston, and Moeller, 1975).

The effects of dirt on Swedish roads has been studied by Rumar and Ost (1974). Dirt primarily covers the markings at a relatively rapid rate. Rumar and Ost (1974) found that pavement markings may lose up to 75% of their retroreflected luminance, from a one-week accumulation of dirt. The effect on daytime visibility was limited. In nighttime, on the other hand, there was a visibility loss of about 30% when using low beams, and about 50% when using high beams. While pavement markings are partly self-cleaning (probably due to rain and wear), pavement markings get dirty together with headlamps. Consequently, the combined effect of dirt on visibility may be substantial. In the study by Rumar and Ost, only the markings were dirty.

3.7.2 Rain and water

Rain is probably the most common adverse condition. When roads become wet, a thin layer of water covers the retroreflective material surface, thereby making most horizontal materials optically ineffective. The smoother the road is, the more sensitive to water the painted markings are. Therefore rough road surfaces offer better visibility for painted pavement markings than smooth road surfaces. One method for combating the deleterious effects of rain is to use larger glass beads in the paint, because the larger beads are tall enough to stand above the thin layer of water. The disadvantage of this approach is that larger beads are also more susceptible to damage and high rates of loss, making them economically unattractive (see Ritter, 1978; Kalchbrenner, 1989; and O'Brien, 1989).

Other methods of raising pavement markers above the water level have also been developed. Profiled markings with vertical parts are less sensitive to the effects of standing water, but have the disadvantage of being vulnerable to snowplow blades (Jingryd, 1995). Raised pavement markers are relatively insensitive to water, with one exception. Some types of snowplowable raised pavement markers are placed in grooves cut into the pavement. As these grooves fill with water, light from the headlamps is reflected off the surface of the water and never reaches the retroreflector, thus the pavement marker ceases to be a visual aid to the driver. Tooke and Hurst (1975) comprehensively evaluated the field performance of a variety of pavement markings available at that time. There was a dramatic decrease in retroreflective performance when the marking became wet, except for prismatic buttons and rod buttons. Indeed, water actually *enhanced* the retroreflective performance of these two latter materials. King and Graham (1989) produced similar results when measuring nighttime wet and dry performance of 15 different materials. Again, while some materials faltered with the presence of water, others actually improved as water volume increased.

Lee, Hostetter, and Leibowitz (1991) also addressed the potential of enhancing night guidance in wet conditions by manipulating the size, shape, and spacing of such markers. Their study found the best performance for large rectangular edgeline post markers, spaced at intervals consistent with the recommendations in the Manual for Uniform Traffic Control Devices. However, these results are to be regarded with caution, because the method involved recognition of road paths for simulated, digitally altered scenes that may or may not have represented actual situations.

3.7.3 Fog and dew

When light from the headlamps, as well as from the retroreflective materials, passes through fog, it is deflected and filtered. Consequently, the retroreflective performance of the materials is reduced. Also, in fog situations, dew is often able to get between the lens and the retroreflective materials, further reducing their retroreflective performance. Dew can form in any moist condition and will have an adverse effect with or without any fog present.

Potash and Brown (1988) evaluated the problem of road delineation and visibility difficulties and suggested the following standards regarding color and placement of raised retroreflective markers: (1) To delineate lanes, use yellow markers on the left and white markers on the right and place at 30 m intervals. (2) To delineate same-direction multilane roads using white markers simulating standard dashed line segments (with 30 m lines, 90 m gaps), place one reflector at the beginning, middle, and end of each line segment. Hagiwara, Yagi, and Seo (1996) attempted to create a delineation treatment that would function well in fog conditions. Visibility was evaluated for a novel laser-beam delineation method in a laboratory-simulated fog. Results showed promise, but the use of the system was not recommended until the practical consideration of developing ways of shielding the system to prevent drivers from looking directly at the beam (while retaining beam visibility).

Blauuw and Padmos (1982) calculated the effects of fog and dew on pavement-marking visibility. They report that a slight fog (sight distance of 1km) reduces visibility of most pavement markings by about 10%, except for dry, raised, reflectorized pavement markings, which are affected more. Heavy fog (sight distance of 0.2 km) results in substantially larger losses in visibility (of about 50%). According to the calculations of Blauuw and Padmos, which are based on extensive light measurements, dew influences are strongest for raised retroreflective pavement markers. They may, in some cases, lose as much as 95% of their retroreflective power when exposed to dew.

3.7.4 Snow and frost

Snow, like dirt, covers retroreflective materials. However, snow has a high luminance factor and is easily visible in automobile headlamps, allowing it to contrast against the darker roads, thus maintaining edge delineation. What is lost is not the lane demarcation effect of markings (except in thick, recently fallen snow, when the lane may be totally lost in a uniform white snowfield), but rather the sign and message components.

Frost is thought to be detrimental to retroreflective markings, but no controlled studies have been found. However, the effect of the frost crystals is to distort the optical properties of the retroreflective materials so that they become inefficient.

3.7.5 Conclusions

Adverse road and weather conditions constitute the “worst case scenarios” for the visibility of pavement markings and are thus deserving of attention. Wear causes loss of and/or damage to the markings, reducing their reflective properties. Advances in durability of materials have decreased this effect to some degree, but pavement-marker damage continues to be a serious issue in areas where markers are vulnerable, such as in cold climates that require the use of plows and/or tire traction aids. Dirt covers the materials, and thus prevents light from entering (and thus from being returned). Markers generally self-clean during rain, but in areas of high roadway dust or low rainfall, additional cleaning measures or considerations of alternative marking approaches (e.g., side-post delineators) may be required. Water blankets the pavement markings with a thin mirror-like sheet that also prevents light from entering the marking, and, instead, reflects the light away from the driver. Profiled materials with a marked vertical relief, which are able to penetrate and rise above the layer of water, have demonstrated remarkable wet visibility. This is especially the case for prismatic and rod buttons. The height of such markers, however, makes them susceptible to damage.

Fog scatters and filters light both heading toward and returning from reflective pavement markers, and may thus reduce visibility. The reductions vary from slight to serious, depending on the thickness of the fog. A new attempt to use laser delineation has shown promise, but it is still in its infancy and many improvements and field validation tests are required prior to implementation. Dew affects the visibility of markers by seeping into the marker and obstructing light as it enters. This can be counteracted with careful assembly and installation of the markers, and the use of sealants with greater durability. Snow covers the markings and prevents them from being seen. Additionally, it alters the visual contrast between the road and the shoulder. This can be partially rectified by more efficient snow-removal. Ironically, it is the snow-removal methods that result in an indirect problem associated with snow—wear and loss of markers because of the use of snow plows and tire traction aids. Efforts to protect the markers with guards that permit plow blades to safely pass over the marker have been effective; protecting them by placing them in recessed grooves is discouraged as these grooves fill with water and limit wet visibility.

3.8 Vehicle and vehicle lighting

Viewing and illumination angles for drivers of heavy trucks and other large vehicles are larger than for drivers of passenger cars, often twice as large. This difference has two effects. It is generally easier to see horizontal markings when you are sitting high above the road. However, the difference between the viewing angle and the illumination angle (the observation angle) is larger and a drawback when it comes to retroreflection. Retroreflectors have their highest performance in situations where this angular difference (the observation angle) is zero. Retroreflective efficiency is reduced as the angular difference increases.

These two effects counter one another such that at long distances the retroreflected luminance and the visibility are approximately equal for drivers of passenger cars and larger vehicles. At shorter distances

drivers of large vehicles lose luminance but gain visual angle. Sivak, Flannagan, and Gellatly (1993) studied road signs and found that truck drivers have nearly the same detection distance to signs as drivers of passenger cars. However, the ability of heavy-vehicle operators to read signs will be worse because the amount of reflected light at distances shorter than 150 m may be less than 25% of the retroreflected light reaching the eyes of a driver of a passenger car at the same distance. The effect of vehicle type on the visibility of pavement markings is not yet known. On one hand the distances are shorter than for road signs, and therefore the retroreflected light difference will be larger. On the other hand, the viewing angle is larger, and therefore the perceived area of the pavement marking should be larger. This problem needs further study.

A change in the illumination from headlamps will change the luminance and the consequent visibility of the pavement markings. This relationship is logarithmic. Consequently a reduction of light intensity by 50% (which is not uncommon due to dirt, corrosion, voltage drop, aging, etc.) is likely to result in approximately a 20% decrease in marking visibility. Most cars have two low-beam headlamps. The incandescent and halogen light sources in the headlamps have a limited lifetime. It is common that only one of the two headlamps is working. A recent study by Sivak, Flannagan, and Miyokawa (1998) indicated that a loss of one headlamp was the second most important factor in real-world headlamp performance, second only to vertical aim.

There are two basic low-beam patterns in use—the U.S. and the European beam patterns. The U.S. low beams provide approximately twice as much light 100 m ahead along the right edgeline (Sivak, Flannagan, and Miyokawa, 1998). According to Helmers and Lundkvist (1991) a four-fold increase in headlamp illumination results in approximately a 40% increase of marking visibility. Consequently, the visibility distance of lane markings using U.S. low beams with no oncoming cars is likely to be about 20% longer than for European low beams. However, U.S. low beams produce approximately twice the amount of glare for oncoming cars (at 50 m). Flannagan, Sivak, Traube, and Kojima (1996) have shown that increasing the seeing illumination by the same proportion as the glare illumination results in a net benefit for seeing. Consequently, there should be a net advantage for U.S. low beams in terms of visibility of road markings.

The low-beam systems are asymmetric. Both U.S. and European low-beam patterns project more light towards the right-hand side than towards the left-hand side. This asymmetry is more pronounced for the U.S. system than for the European system. Consequently, drivers should be able to see lane markings farther on the right-hand side than on the left-hand side (in right-hand traffic). Zwahlen and Schnell (1995) found that in situations with oncoming traffic this difference in visibility is increased because the angle between the target and oncoming glare is larger on the right-hand side.

Pavement markings tend to appear below horizontal and from seven degrees to the left to seven degrees to the right in the visual field. This should be taken into account in the design of the headlamps, because any possible means to enhance pavement-marking visibility should be explored. Projecting more light from the high- and low-beam light distributions in the direction indicated is one such approach to enhance visibility.

Driver eye position also influences nighttime visibility. As eye height increases, so does the corresponding detection distance of lane markings (under otherwise constant conditions). As eye height increases, it is easier to interpret the course of the road as indicated by the lane markings (Godthelp and Riemersma, 1982).

Another vehicle category deserving attention is motorcycles. Motorcycles normally have either one normal headlamp or two small headlamps resulting in considerably less available headlamp illumination than is the case for cars. To maintain balance, riders must tilt the vehicle in curves, a practice that changes the beam pattern on the road. Also, to motorcycle riders, road guidance is likely to be more critical than for car drivers. They have, however, one small advantage over drivers of other vehicles. Specifically, the observation angle for relevant targets is smaller than is the case for car drivers. This results in improved effectiveness of retroreflective materials, including markings.

Riders of bicycles need pavement markings at least as much as drivers of motorized vehicles. Due to their relatively limited speed, the markings do not have to be visible at long distances. However, the lighting performance of bicycles is poor. Most bicycles in night traffic do not have front lights, and those that do exist are designed more for the purpose of allowing bicyclists to be seen by others than to see by. Thus, to provide effective guidance, pavement markings would have to possess high retroreflective performance to be useful to bicyclists.

3.9 Driver condition

While it may be cost effective and appear to have high face validity to design pavement-marking policies for the average driver, it is also imperative to consider and accommodate other driver populations possessing special needs. Examples of such groups include older drivers, drivers under the influence of alcohol and drugs (DUI), fatigued drivers, and visually impaired drivers.

3.9.1 Older drivers

The proportion of drivers over the age of 60 is increasing. While older drivers tend to self-select themselves out of nighttime driving situations, an increase of older individuals driving under nighttime conditions is inevitable. This presents a potential problem because older drivers tend to suffer cognitive limitations. Such limitations include distractibility, indecision when presented with novel situations, and delayed reaction times (Rumar, 1998). Added to the mental changes are physical changes that require greater retinal illumination to trigger detection (Owens and Tyrell, in press). The design of pavement markings should reflect these increased visual needs of older drivers. Pietrucha, Hostetter, and Staplin (1995) investigated twelve marking treatments and found that the combination of a 10-cm-wide yellow reflective tape centerline, 10-cm-wide white reflective tape edgeline, and full reflective T-post edge delineators spaced at MUTCD intervals yielded the best curve detection among older drivers. Financial

concerns, however, prompted them to recommend a similar system but without the 10-cm-wide white reflective tape edgeline.

In their study of lane-marking visibility, Zwahlen and Schnell (1996) found that the detection distances for senior drivers were 45% shorter than those for young drivers. Graham, Harrold, and King (1996) performed a study investigating the visibility and reflectance needs of the older driver. They found that a minimum reflectance level subjectively deemed adequate by older participants was 100 mcd/m²/lux. Recognizing that the test evaluation occurred during relatively good conditions, the authors recommended that the reflectance level should be increased by 21% to overcome such factors as dirt or fog on the headlamp lens covers or the windshield. Thus a minimum reflectance level of 121 mcd/m²/lux was recommended.

3.9.2 Driving under the influence

Alcohol reduces cognitive, perceptual, and motor abilities resulting in improper judgements, missed detections, and slower reactions. A publication by Potters Industries, Inc. (1981) reported research conducted to evaluate the use of wide edgelines as an aid for visual guidance of alcohol-impaired drivers. The results indicate that as edgeline width increased (from 10 cm to 20 cm), drivers maintained a more consistent lateral distance from the edgeline marking.

Johnston (1983) investigated curve negotiation of drinking drivers as a function of roadway delineation treatments. It was found that alcohol-impaired drivers initiated a higher rate of corner-cutting techniques. These driving tactics were initiated too drastically (overcompensation) and too late into the curve, resulting in a higher incidence of lane departures. It was suggested that these maneuvers were initiated because the direction and radius of the curve were realized late. In general, addition of increased pavement-marking navigation aids resulted in a lower speed at the entrance end of the curve, suggesting earlier detection of the curve characteristics. The use of chevron post delineators was found to result in higher curve-entrance speeds and more drastic curve-cutting procedures. A hypothesis was presented suggesting that the chevron alone gave a false sense of security based on knowledge of the direction of the curve, but the drastic maneuvers were later required because the drivers lacked planning knowledge for the radius of the curve. Best performance was achieved when chevron signs and wide edgeline-delineation treatments were combined.

Earlier in this report an analogy was made between handrails and lane markings. This analogy may be appropriate for drunk drivers in night driving as well. Impaired drivers are more common in night traffic and they are likely more dependent on good lane markings than other drivers are.

3.9.3 Degraded visual performance

Many additional factors alter an individual's ability to see well at night. Impaired visual capabilities may come, for example, in the form of reduced contrast sensitivity (degradation in one's ability to detect

and/or distinguish elements in the environment), or night myopia (nearsightedness exhibited in low-illumination environments). (See Allen (1984) for a general discussion of such visual deficits.) However, no studies exist on the effects of such deficits on nighttime driving performance or visual requirements of pavement markings. Consequently, proper scientific inquiry should be conducted in this area.

3.9.4 Fatigue and distraction

Other special-needs drivers are those with reduced attention, such as physically or mentally fatigued drivers, or drivers distracted by other tasks. Physical and mental fatigue interferes with the ability to detect, process, and act upon information critical to navigation and obstacle avoidance. Task diversion is of growing concern in the current technological age. Increased complexity of driver information systems (electric navigation aids, etc.), the use of communication equipment (cellular phones, etc.), and eating and drinking are common during driving. Each works to reduce the attention resources available to the driver, possibly resulting in missing environmental cues vital to safe travel. Research evaluating the nighttime visual needs of these drivers is markedly absent. Given the suspected high proportion of drivers at night that suffer some degree of attention reduction, it is recommended that studies should be carried out to investigate how such driver populations could best benefit from improved lane-marking systems.

3.10 Friction, noise and other performance factors of lane markings

A safety-relevant aspect of pavement markings that is often overlooked is that most of the pavement markings reduce friction. This is of limited interest to cars and drivers, which always have at least one pair of wheels not on a marking, but may be of substantial importance for two-wheelers, such as bicycles and motorcycles. In wet conditions, the reduced friction may affect the stability of two-wheelers. Many pavement-marking regulations and standards have requirements for friction, but no studies of this problem have been located.

Profiled lane markers have been mentioned several times, especially in connection with their comparatively good performance in wet conditions. However, they also have another good property. They cause noise when they are driven on. Some standards even mention suitable noise levels for such profiled, rumbling markings.

3.11 Durability, maintenance, and costs of markings

The durability of pavement markings is well documented in the literature; in fact, a large portion of studies performed prior to 1980 that compared materials used effective longevity and cost effectiveness as primary criteria for recommendations. While the durability and wear/damage resistance have direct impact upon the reflectance, and therefore the visual guidance, offered by the materials, these aspects were considered of lesser relevance to the overall scope of this report. As a result, such considerations are

treated only briefly. Table 8 provides a summary, based on the following publications: McGrath, 1981; Agent and Pigman, 1983; McNees and Noel, 1986; Tielking and Noel, 1989; Paniati and Schwab, 1991; Miller, 1992; Chapman, 1994; Migletz, Fish, and Graham, 1994; and Perrin, Martin, and Hansen, 1997.

The earliest and most common form of roadway delineation involved painted lines. This approach is well suited for daytime road delineation. A problem with typical traffic paint is that it offers very poor nighttime visibility. This is greatly enhanced with the application of glass beads, but beads are susceptible to loss and wear, severely deteriorating visual performance. Additionally, when wet water collects on top of the paint, visibility of the line is partly or completely lost. While paint offers low initial costs, frequent maintenance quickly increases its overall cost.

Thermoplastics have gained in popularity because of increased life compared with that of traditional paint, and they offer good night visibility and better visibility than painted lines in wet conditions. The thickness of the material keeps it above shallow standing water, which normally renders painted lines invisible. Thermoplastics, however, are susceptible to damage from snowplows.

Preformed tape lines have the same benefit of thermoplastics in that they are thick enough to stand above shallow water, and thus possess better wet visibility than painted lines. Unlike thermoplastics, they conform better to the pavement, and are thus less likely to be damaged by plows. This advantage comes at a price. It has been noted that in areas of high traffic volume, or where high rates of lane changes are prevalent (e.g., near an exit ramp), the material may tend to shift.

Epoxies are typically used in areas where cold weather makes other treatments difficult to use because of the potential for plow damage. Reflectance tests indicate that they still remain effective after a year of wear and plow use. Costs of routine maintenance, long curing times, and installation procedures that are unforgiving of errors are the negative factors associated with the use of epoxies.

Polyesters are of relatively low cost and have consistent performance over many years of service. Additionally, they can be easily applied on top of existing markings with little or no pavement preparation. However, they require long drying times, and the chemical catalyst used during application is toxic and must be handled with extreme care.

Epoflex is the name given to the epoxy-thermoplastic hybrid material. It has remarkably short dry time (about 5 s). This property, while making it attractive for quick installation and for minimizing traffic disruption by work crews, also makes it difficult to time the application of drop-on beads for reflectivity. If the material is too dry when the beads are added, they will not adhere to the surface and the treatment reflectivity will suffer greatly from bead loss.

Table 8
Comparison of major pavement marking techniques.

Marking Material	Life span	Unit Costs*	Advantages	Disadvantages
Paint	•1-3 yrs. cold	1	•Easy installation •Low initial cost	•Short life span •Poor wet-night visibility •Year-round delineation in severe weather areas may be impossible
Thermo-plastic	•1 yr. cold •10 yrs. warm	10	•Good dry visibility •Long life span (warm)	•Short life span (cold) •Sensitive installation
Preformed tape	•2 yr. cold •8 yrs. warm	13-20	•Easy installation •Long life span (warm) •High reflectance •Long color life •Short traffic disruption •Easy to repair	•May shift under high traffic volumes
Epoxy	•1-5 yrs.	8	•Less energy to apply •Effective 12 mo. reflectance (lasts winter)	•Long cure time •Very unforgiving installation •Special equipment required
Polyester	•3-4 yrs.	5	•Consistent performance •Low cost •Applies over existing markings	•Long dry times •Abrasion/bond failure problems •Careful handling of catalyst •Mixture of components must be set precisely
Epoflex	•2 yrs. cold •10 yrs. warm	1	•Low cost •Minimal traffic disruption •Quick dry •Can be applied in low temp •Long life span •Good reflectance	•High installation temp. •Requires new equip. •Short time window for bead application to ensure good bonding
Raised markers (studs)	•1-20+ yrs.	?	•Potential long life span •Excellent night visibility •Excellent wet visibility	•Poor day delineation •Only spot delineation •Vulnerable to plows •Higher initial cost

*Unit costs were employed due to the changing nature of monetary values. Estimates in U.S. dollars per length collected from several articles were used to calculate the relative relationship among the treatments. Numbers represent multiples of cost; a rating of 5 indicates a relative cost being five times the cost of a product rated as 1.

Raised pavement markers have gained widespread popularity primarily in warmer climates due to their excellent nighttime and wet visibility. Their high profile allows them to retain reflectivity in deeper water than other treatments. This characteristic, however, is their downfall in colder climates where damage from plows severely affects the retention rates and reflective abilities. To counteract this, ceramic or metal shields have been used to allow the plow blade to pass safely over the reflector without damaging it. Loss in this case comes primarily from pavement fault as the pavement the shield is attached to breaks away. Attempts have also been made to protect the markers by inserting them into the pavement. While this protects them from plow damage, placing them in grooves negates their wet visibility as the grooves fill with water. Shape influences marker loss; round markers are found to be retained longer. Cost for this treatment was not entered into the above table because raised markers are primarily used for spot delineation in combination with other treatments (partly to create a system that is visible during both day and night) and not solid or long-dash markings. While it is not directly comparable to cost measures for other products, each individual marker may cost anywhere from 50 to 2,500 times that of 30 cm of paint. This seemingly overwhelming cost is often made up for by comparatively excellent visibility and a near limitless life span when properly protected.

3.12 Regulations and standards

This section is based on the most up-to-date regulations found in the literature, and on the proposed European standard for pavement markings, which is expected to be adopted shortly.

There are three levels of standards concerning pavement markings. The first step consists of specifying the design, dimensions, and color of pavement markings for different purposes. The road users should always be able to trust that a specific marking has the same meaning. The goal is to reach uniformity. The second step involves introducing technical specifications for the materials. The goal here is to facilitate laying out the markings and to guarantee a minimum level of durability. The third step consists of specifying photometric and other road-safety requirements. The goal is to make certain that the markings fulfill certain minimum road-safety standards.

The desirable dimensions of various pavement markings in a variety of situations are discussed by Freedman, Staplin, Gilfillan, and Byrnes (1988) and ECTM (1975). These documents cover such topics as lane width, stroke length, gap interval, thickness and color for edgelines, centerlines, and lane markings on various types of roads.

The European standard also contains a number of technical performance requirements (CEN, 1996). For example, it addresses types of beads, resistance to wear, deformation characteristics, softening points, alkali resistance, cold impact, heat stability, UV aging, and adhesion properties of various types of pavement markings on different types of roads. The compliance of 21 thermoplastic materials with these physical requirements was tested by Edwards and Astrom (1997). None of the spray plastic markings passed all tests, and only three of the extruded plastic markings passed all tests. The corresponding U.S. technical standards are specified in various ASTM documents.

Most European national standards and regulations require minimum performance of the pavement markings concerning these aspects:

- luminance coefficient under diffuse illumination (Q_d)
- coefficient of retroreflected luminance (R_L)
- skid resistance
- functional life
- luminance factor (β) and color coordinates (when relevant)

The almost completed European Union Standard (CEN, 1997) was produced by the Technical Committee CEN/TC 226. When it becomes a European standard, it will be compulsory for the 18 CEN members (the 15 members of the European Union, plus Norway, Iceland, and Switzerland). This standard specifies the performance of white and yellow pavement markings, as expressed by their reflection in daylight and under road lighting, retroreflection in vehicle headlamp illumination, their color, and skid resistance.

The following four parameters are the main variables specified in the European standard:

Luminance coefficient under diffuse illumination (Q_d) expressed in $mcd/m^2/lux$. Q_d is the quotient of the luminance of the pavement marking and the illuminance on the pavement marking. Q_d represents the brightness of a pavement marking as seen by a driver in typical daylight or street lighting conditions. The observation angle is 1.05° and the pavement marking has an area of at least 50 cm^2 . The measuring condition is supposed to simulate an observer distance of 30 m and a driver eye height of 1.2 m above the ground. A simplified way to measure the brightness of the pavement marking is to measure the luminance factor of the marking (β) when illuminated in an angle of $45^\circ (\pm 5^\circ)$ and measured at an angle of $0^\circ (\pm 10^\circ)$.

Coefficient of retroreflected luminance (R_L) expressed in $mcd/m^2/lux$. R_L is the quotient between the luminance of the pavement marking in the direction of observation and the illuminance at the pavement marking on a plane perpendicular to the direction of the incident light. R_L represents the brightness of a pavement marking as seen by a driver at night when the pavement marking is illuminated by standard headlamps. The (U.S.) observation angle is 1.05° (the European observation angle is 2.29°), and the illumination (co-entrance) angle is 1.24° . The size of the pavement marking is at least 50 cm^2 . The measuring condition simulates an observation distance of 30 m with the eye height of the driver 1.2 m above the ground and the headlamp mounting height of 0.65 m.

Skid resistance of the pavement marking. The skid resistance is measured on wet pavement markings by the friction of a rubber slider with the surface. The equipment used is a British Skid Resistance Tester (SRT) (RRL, 1960).

Functional life of the pavement marking. The functional life is defined as the period during which the marking fulfills all requirements initially specified by the responsible road authority.

Minimum Q_d values are specified for white and yellow markings on two classes for asphalt and concrete roads. The values for dry markings range from 80 to $160\text{ mcd/m}^2/lux$.

The minimum values for the luminance factor (β) range from 0.2 to 0.6. White and yellow colors are specified by corner points of their chromaticity regions. There are two specifications for yellow (permanent and temporary).

Minimum R_L values are specified for white and yellow when used with one of four classes of asphalt and concrete roads, and for three classes for temporary markings. In dry conditions the minimum values range from 80 to 300 mcd/m²/lux. In wet conditions (1 minute after flooding) and in rainy conditions, the coefficient of retroreflected luminance values range from 25 to 50 mcd/m²/lux.

The friction values are specified for six classes of markings and range from 45 to 65 SRT.

Various ASTM documents specify how photometric measurements of pavement markers (both lines and raised markers) should be carried out. Although the definitions are somewhat different, the ASTM specifications look similar to the European specifications. However, as of yet, there are no U.S. federal photometric standards for lane markings. Many states have, however, implemented such requirements independently.

Europe is approaching a standardization on photometric measurements and requirements for pavement markings. Should there be activities towards international harmonization of standards before any regional requirements are set? Or are the differences between roads, vehicles, and traffic so large that it would be unrealistic to come up with the same sets of requirements? Regardless of the answer to this question, it would be worthwhile to agree on the definition of the parameters, the testing procedures, and the type of suitable requirements.

4. SUMMARY OF MAJOR ISSUES AND SUGGESTIONS FOR FUTURE RESEARCH

This section will summarize the previous material and will suggest topics for future lane-marking research. Because this section will cover literature previously surveyed, the appropriate references will, generally, not be repeated.

4.1 Which criteria should be used to evaluate pavement markings?

Previous studies employed many different criteria for evaluating lane markings. One of the most frequently used criteria was accident rate. In spite of a large number of studies, the results are not conclusive. The problem may lie in the complexity of accident causation and/or the complexity of the effects of pavement markings.

Efforts to evaluate various lane-marking designs using behavioral variables (e.g., speed, lateral position on the road, and the number of overtakings) have met with little success, because the results are conflicting and the interpretation of the results is often subjective. Also, the relationship between visibility and behavioral measures is unclear.

Subjective evaluations have yielded better results. However, no direct comparisons between subjective and objective visibility have been made. Also, it is difficult to say what the subjective evaluations are based upon. Perhaps it is a weighted function of perceived comfort and visibility. However, comfort and visibility estimations may be based both on long-range and short-range visibility, or on a combination thereof. The uncertainty concerning this issue creates a problem for subjective evaluations of pavement markings.

In this review we have chosen visibility, as determined by detection distance, as our main criterion for the evaluation of lane markings. This was done for several reasons. First, our belief is that poor visibility of lane markings is their main weakness. Marker visibility is not acceptable in normal night driving, and even worse in degraded conditions. Second, visibility determined by detection distance is comparatively objective and insensitive to confounding factors. Third, visibility is closely related to the retroreflective performance of the lane markings. Fourth, because of this relationship between photometric properties and visibility, it is possible to develop useful visibility models.

Detection distance is probably the most important aspect of visibility, but it is a threshold measure. Another type of visibility is suprathreshold visibility. This refers to the visibility of the markings within the detection distance range. This may be of interest if there are two types of road guidance (i.e., short-range and long-range).

The qualitative question of suitable criteria to evaluate pavement markings needs to be further studied. The quantitative question of minimum retroreflective performance is discussed in Section 4.8.

4.2 Is there a need for improved visual guidance at night?

Section 2 concluded by stating that there are two views regarding the need for improved visual (road) guidance in night traffic: for it and against it. The literature did not provide any clear-cut answers, only arguments defending the respective positions. These positions can be summarized as follows.

Arguments for the need to improve visual guidance

- Visual guidance at night is considerably less effective than during the day.
- Driver models suggest that the perception of the road is critical for driver performance because it is a prerequisite for driver predictions. (This conclusion is supported by results from studies of driver behavior.)
- Drivers list impaired road guidance as the main problem they face in night traffic.
- Results from studies of driver eye movements show that drivers' attention and visual fixation move closer to the vehicle in night driving relative to day driving.
- Accident reductions as a consequence of pavement markings appear primarily in night traffic.
- The rate of single-vehicle accidents (running off the road) at night is between two and three times higher than during the day.
- This difference in accident rate increases when the visibility of the road degrades.

Arguments against the need to improve visual guidance

- One of the factors behind the higher accident rate at night is that recognition visibility is more impaired in night driving than is guidance visibility. (This is based on the hypothesis that there are two visual functions in driving—guidance and recognition.) Overconfidence would become even worse if guidance were improved.
- The self-pacing character of driving at night is primarily governed by road guidance, not the level of recognition. Indeed, a number of studies show that speed is increased when guidance at night is improved.
- According to a single Finnish study, accidents increase when guidance at night is improved by the use of retroreflective post-mounted delineators.

Both positions have valid arguments, and both acknowledge that road guidance and recognition are seriously impaired at night. The fact that the need for improved recognition visibility is greater is an argument for such improving recognition, not an argument against improving road guidance. It is not that road guidance systems are too effective, but rather that recognition conditions are too poor. Thus, the recommended course of action is to work towards improvements in both recognition and guidance.

4.3 Are there both long- and short-range road guidance?

Theoretical arguments and empirical results indicate that drivers make use of two complementary road-guidance functions, involving short-range and long-range guidance. Long-range guidance requires more than 5 s of preview time, while short-range guidance requires less than 3 s.

When drivers use only the short-range road guidance, it is because the long-range road guidance is unavailable. The most common such situation involves night driving on dark roads. From a road-guidance point of view, a more difficult driving situation is driving in thick fog. In low-visibility conditions, the task of the driver is not to predict the course of the road, but rather to properly navigate within the roadway boundaries. In such situations the driver needs to see the road in order to maintain safe guidance. A transition from combined long-range and short-range guidance to short-range guidance alone results in using the nearby lane markings in central vision (frequently and consciously). This is demanding and requires additional mental resources.

The purpose of the long-range visual guidance function is primarily to make it possible for the driver to predict the route of the road and to drive smoothly without too much demand on mental resources. Long-range visual guidance enables the driver to predict the road consciously in central vision, to see what will happen far in advance, and to avoid time-pressure situations. The driver can follow the road, to a great extent, by the use of peripheral vision and without engaging higher-order cognitive centers. This is easy during daytime, but difficult at night.

The existence of two complementary road guidance functions could explain why combinations of several marking systems (e.g., pavement markings and side-post delineators) are more successful in reducing accidents (see Table 1). Such combinations supply both long-range and short-range road guidance at night.

4.4 The gap between driver visual needs and lane-marking performance

Comparing drivers' road-guidance needs with the visibility provided by present lane-marking systems indicates that current road delineation systems are not sufficient. It is concluded that drivers need about 5 s visibility in order to drive smoothly and not be surprised. A preview time of 5 s corresponds to a distance of 140 m at a speed of 100 km/h.

In many daylight conditions this desired visibility level is not always reached (see Table 3). In other words, even under the best visibility conditions (daylight) the safety criterion is not reached. In less favorable daytime visibility conditions (e.g., with glare from the sun) performance will be worse. However, it may be argued that lane-marking visibility is critical not during the day, but rather during darkness and other low-visibility conditions.

Let us turn our attention to Tables 4 and 5, which present typical nighttime visibility distances for lane markings obtained in field studies. Because they are obtained experimentally they are likely to be longer than visibility distances in actual traffic. On the other hand, many of the studies used dashed lines

as targets and that might have shortened the detection distances. Table 4 indicates that under high-beam conditions, the safety criterion is sometimes reached. But, in general, the visibility distances provided with high beams are still too short to be considered safe.

The situation for low beams, as presented in Table 5, is of even more concern. Visibility distances of only one-third of the minimum safety criterion are provided to the drivers. Driving on low beams is, by far, the most common driving situation at night. The glare effect of oncoming low beams is limited. The detection occurs well within the high-intensity area of the low beams, making it fairly independent of glare. It is sometimes questionable whether low beams offer even short-range road guidance.

Many of the pavement markings used in these studies reach the existing photometric requirements. However, it appears that in the past requirements have been set with consideration of the existing technologies. Specifically, requirements have been specified to be well within obtainable limits. Also, the regulations are often obsolete as soon as they are published due to the delays in coming to agreement. Given existing improved retroreflecting technologies, it might be timely to eliminate or at least reduce this gap between demand (needs) and supply concerning visibility of pavement markings.

4.5 Difference between dry and wet lane-marking performance

One of the most critical and most difficult situations in night driving involves rain. The road itself loses visibility because water covers it, causing light from the headlamps to be reflected away. Glare from oncoming cars is multiplied by the reflection of the light from the wet road surface. In such situations, drivers have more need than ever for good road guidance by means of lane markings. However, it is precisely in such situations that the existing pavement markings generally exhibit their worst performance.

Tables 4 and 5 demonstrate the decrease in lane-marking visibility that occurs as an effect of wet road surfaces. Rain further reduces driver visibility due to water drops on the windshields, on the headlamps, and in the atmosphere. The gap between visibility needs and visibility supply is even more pronounced in wet conditions.

Efforts have been made to meet the need for improved road guidance at night in wet conditions by designing lane markings that are profiled, and that have retroreflective elements that protrude above the mirroring water surface on the road. The results from the existing limited field trials indicate that the markers work well and that it is possible to maintain high visibility levels in both dry and wet conditions (see Table 7). However, Table 6 also indicates that profiled lane markings are more sensitive to wear than flat pavement markings. Even so, they maintain their superiority in wet conditions after considerable wear.

Calculations concerning raised pavement markers indicate that they are superior to profiled markings in wet conditions (see Table 7). Other studies point out that the performance of studs often improves in wet conditions (possibly because water cleans the lenses). However, studs are also sensitive to wear. A particular durability problem for studs is snowplows.

This difference between visibility of lane markings in dry and wet conditions should be eliminated or at least reduced. There are some new promising technological solutions, but more research and technical advances are needed.

Additional wet conditions include fog, dew, and frost. However, there is only a limited amount of existing research on the functioning, visibility, and usage of lane markings in such situations. Fog is believed to be a condition in which drivers have a great need for good road guidance, and thus lane markings could be especially helpful in such situations.

4.6 The relation between retroreflective properties and visibility

Results from a variety of studies consistently show that the visibility of pavement markings is related to the logarithm of their retroreflective performance. This pattern was obtained for studies of objective as well as subjective visibility, in dry and wet conditions.

Correlation coefficients between log retroreflected luminance and visibility ranged from 0.70 to 0.95. These results are based on measurements of retroreflective performance corresponding to the standard geometry. Furthermore, evidence suggests that the correlation might be even stronger if retroreflective performance were measured in a geometry corresponding to actual detection distances. However, it is not clear whether there is a specific logarithmic relationship for each special situation.

4.7 Computational models of marking visibility

There are at least three computational models for estimating the visibility distance of pavement markings. The CIE model (CIE, 1988) appears inadequate, judging from the comparisons in Table 6. The CARVE model (Schnell and Zwahlen, 1997) has been calibrated and validated. According to the authors, it is now quite effective, but it is presently not available for general use.

A widely available model has been developed by Sorensen from the Danish Lighting Institute (DELTA) within a European cooperative research program called COST (Sorensen, 1998). It is a modular model, consisting of modules related to the driver, vehicle, glare, road geometry, headlamp illumination, coefficient of retroreflected luminance (R_L), daylight/street lighting, and the luminance coefficient in diffuse illumination. In each module it is possible to enter various alternatives. This model has been validated against field measurements of visibility carried out at the Swedish Road and Transport Research Institute (VTI) with very promising results. However, like all models, it contains a number of simplifications. For instance, the headlamp model only considers European beam patterns, and the representation of the pattern is fairly simplistic.

We have used this model to calculate visibility distances in a number of situations corresponding to the conditions used by studies referenced in Section 3. We also varied the coefficient of retroreflected luminance ($R_L = 50, 100, 200, 400, \text{ and } 800 \text{ mcd/m}^2/\text{lux}$) measured in the standard geometry. The following parameters were used:

- driver age: 30 years
- traffic: right hand
- vehicle: passenger car
- headlamps: European low beams and high beams, intensity 1.00
- glare: no
- road: straight, flat, no lighting, 4 m lane width
- R_L of road surface: 15 mcd/m²/lux
- marking: right edge and centerline, 0.1 m wide, dashed, 10 m long, 5 m gaps

The results are shown in Table 9. The obtained distances are longer than one might expect, but are consistent with the empirical field data on visibility as presented for new markings in Tables 4 and 5.

Table 9

Visibility distances as obtained using the visibility model presented by Sorensen (1998) for centerlines and edgelines with high beams and low beams. (See the text for other parameters used.)

Coefficient of retroreflected luminance R_L (mcd/m ² /lux)	Low beams	Low beams	High beams	High beams
	Edgeline	Centerline	Edgeline	Centerline
50	63 m	53 m	66 m	66 m
100	81 m	58 m	90 m	90 m
200	93 m	64 m	114 m	114 m
400	104 m	78 m	142 m	142 m
800	114 m	97 m	172 m	172 m

The three models mentioned have many common features, but they were developed and calibrated in different ways and thus provide different results. No impartial comparison of the three models exists.

There are many properties of these models that deserve to be studied. Of primary interest is their validity. However, the validity may be expected to change depending on the situation. One model may be better for one condition, or situation, while another model better for a different situation. This would depend on how sensitive the respective models are to changes in various variables. Additional research is needed before we can start using any of these models in applied situations.

4.8 Minimum reflective performance of lane markings

As was discussed above, the process of developing regulations and standards of pavement markings has gone through three phases. The first phase deals with the uniformity of the designs and the messages. The second phase concerns the minimum physical quality of the markings to ensure acceptable durability

and reasonable costs. In the third phase, which is still in progress in most countries, the goal is to set standards for safety.

This means that requirements are specified primarily in terms of the photometric characteristics of pavement markings. The most important lane-marking property for safety in night traffic is retroreflective performance. In technical terms, that means the coefficient of retroreflected luminance for pavement markings (R_L) and the coefficient of luminous intensity (R_I) for raised pavement markers. But, despite considerable research there are still no generally accepted minimum levels of retroreflective performance.

Ideally the retroreflective performance of lane markings should be based on driver needs. In Section 3.5.4. it was stated that a minimum visibility distance to achieve smooth and safe drive behavior, and to adequately detect the route ahead, is 140 m. This distance should be the same for most driving conditions and, preferably, it should be longer in degraded or especially difficult situations. Unfortunately, the existing pavement markers do not reach these requirements under good conditions and are even worse in degraded conditions, such as rain. Other, less important, properties for pavement marker performance in night traffic are brightness, or luminance factor, and friction.

Present standards accept the existing technical difficulties and specify lower retroreflective values for wet pavement markings. This is a compromise between demand and supply. The corresponding type of compromise is evident when comparing new and old proposals for minimum retroreflective performance. The initial proposals, dating back to the 1970s (Allen, O'Hanlon, and McRuer, 1977) involved a minimum coefficient of retroreflected luminance for new materials of about 90 mcd/m²/lux. In the early 1980s (Serres, 1981) the recommended minimum reflectance in the same situation was 150 mcd/m²/lux. In the late 1980s (Ethen and Woltman, 1986) the recommended minimum value for new materials was 400 mcd/m²/lux. In the proposed present European standard (CEN, 1997) the recommended value is 300 mcd/m²/lux. However, that value refers to the replacement value (see below).

Durability is one of the main pavement-marker problems. Therefore, while it is important to have requirements for new markings, it may be even more important to also have requirements for worn markings. Serres (1981) proposed a minimum for replacement of 100 mcd/m²/lux. Ethen and Woltman (1988) agreed. But, as indicated above, in the present European proposal (CEN, 1997) this value is raised to 300 mcd/m²/lux for the highest class of markings.

The requirements for wet pavement markings followed a different trend. Serres (1981) proposed 60 mcd/m²/lux. In the current European proposal (CEN, 1997) this value is generally lower—between 25 and 50 mcd/m²/lux. However, for safety considerations, instead of being lower the wet requirements should be higher.

Another problem is that the standard measuring geometry that is now emerging corresponds to a distance of 30 m to the marking. This will favor markings that give high values at that short distance. That is unfortunate because it should be an advantage if the retroreflective properties of markings could be tailored in such a way that their performance increases with increased distance from the vehicle.

Even if headlamp beam patterns and traffic conditions in general vary between countries and continents, international agreement on minimum requirements for pavement-marking retroreflectance

characteristics would be desirable. Drivers would meet the same lane-marking characteristics regardless of where they drive. Additionally, pavement-marking companies that sell their products worldwide would benefit from uniform requirements.

From a safety point of view (visibility beyond 140 m using low beams with oncoming low beams) the presently proposed values are too low. Lane markings reaching 300 mcd/m²/lux may be visible at the absolute minimum (84 m), but we cannot be satisfied with a situation where the standard is at the absolute minimum level. That would require all elements (marking, driver, vehicle, weather, etc.) to be in ideal conditions—a situation not obtainable in the real world! Rather than 300 mcd/m²/lux, the minimum should be at least 1000 mcd/m²/lux for high-class markings to allow a reasonable margin for variation and degradation. The requirements in wet conditions should be even higher than in dry conditions.

4.9 Color, dimensions, and configuration of lane markings

The design of the pavement markings has one obvious purpose—to transmit a message to the users. However, the design characteristics also influence the visibility of the markings and the general behavior of drivers. One problem is that the meaning of the various design characteristics are not internationally standardized. There might have been reasons for national differences at one time, but it is now time to reduce the differences. The situation resembles that of road signs. However, changes to pavement markings would be easier, because their shorter life span could allow these changes to be implemented incrementally as a part of normal maintenance and replacement programs.

Color coding undoubtedly affects drivers' behavior by transmitting a specific message to the road user. However, every color returns less light than the corresponding white. Secondly, when luminances are reduced as distances increase, the driver's ability to recognize various colors is also reduced. Finally, some road users are color-deficient and their ability to understand the message of some colors may be reduced. Therefore we must not rely too much on color coding.

The use of solid and dashed lines, or a combination of line configurations, may also be used to transmit messages to users. The problem is that because the angles at which drivers of passenger cars see the lines are small ($< 1^\circ$) it is difficult to perceive differences in line configuration at distances that would allow drivers to plan for changes in the road ahead.

For line visibility in night driving, the amount of light reflected back to the driver is critical. The amount of reflected light may be influenced by the type of retroreflective material, by the width of the marking, number of lines, color, and other characteristics. The configuration is of a lesser importance.

4.10 Combinations of various marking principles

The accident studies (see Table 1) clearly show that combinations of markings are more effective than any component marking system alone. However, it is not known which markings work well together and what are the optimal combinations for different purposes and conditions.

It was suggested above that the reason for further accident reduction with the combination of lane-marking systems is that they offer both short-range and long-range road guidance, and thus the drivers are supported in both good and poor visual conditions. Another possibility is that combinations of systems increase the stimulus intensity and that the effect is quantitative rather than qualitative. A large number of combinations are possible. The potential elements include traditional lane markings, profiled line markings, raised pavement markers, chevrons, and a large number of various road signs.

4.11 Flat versus profiled lane markings

The visibility of lane markings in wet conditions is one of the weakest points of lane-marking performance. One possible remedy involves the use of raised pavement markers, which often offer better visibility in rain than flat markings. They have, however, several drawbacks such as high price, vulnerability to snowplows and traction aids in winter conditions, and offer poorer short-range road guidance.

Another way of reducing this problem could involve the use of profiled pavement markings. Profiled pavement markings are normal plastic lines, which are modified to have a relief. The relief may be created by stamping a pattern in the line, by equipping the lines with special vertical elements, or by adding an intermittent marking to the outside edge of the line. The vertical element protrudes above the water surface and maintains higher retroreflective performance in wet conditions.

The profiled lane markings work well in wet and dry conditions when new. However, they are more vulnerable to wear than flat lane markings. After a number of seasons, their superiority in wet conditions is reduced and, in some cases, nonexistent. Additional technical development is required to enhance their resistance to damage and wear.

4.12 Line versus spot marking of lanes

There are two major types of lane markings for night traffic, traditional retroreflective lines and retroreflective point sources. The point sources are usually called raised pavement markers or studs. Studs are positioned horizontally on the road surface, but project above it and have a retroreflective surface that is mounted at an angle of about 45°. Conceptually, raised pavement markers lie between traditional markings and side-post delineators. They offer better long-range road guidance than traditional lines and superior wet visibility. Their main drawbacks are durability and cost.

Often spot marking and line marking are combined. This makes sense because line markings can be used to provide short-range guidance and good delineation during the day, and raised markers offer better long-range guidance and wet delineation. However, no studies exist on the best combinations.

4.13 Lane markings on straight roads and on curves

Lane markings were first used to augment curves because it was perceived to be important to provide lateral separation between oncoming vehicles in curves, and to inform the drivers in advance about the presence of the curve so that they could choose a safe speed.

As discussed earlier in this report, improved lane-marking performance may have the disadvantage that drivers overestimate their visibility and drive faster than their actual visibility distance would allow. This could be the situation on straight roads. The purpose of better markings on curves, however, is primarily to improve driver estimation of the route of the curve in order to be better prepared and to facilitate a safe driving speed through the curve. However, the data on the effects of lane markings on speeds in curves are limited and not consistent, and thus more research is needed to establish reliable relationships.

Another related question is whether lane markings on curves should be different from those on straight roads. For example, should the lines be wider, or should complementary systems such as raised pavement markers and side-post delineators be used differently on curves as opposed to straight roads?

4.14 Vehicle aspects of lane markings

Several vehicle aspects influence the visibility of lane markings. The type of vehicle driven (passenger car, heavy truck, motorcycle, etc.) alters the viewing geometry. The entrance angle of the light from the headlamps towards the markings is influenced by headlamp mounting height. The observation angle (the angle between the illumination axis and the viewing angle) is also a function of headlamp mounting height. The beam pattern of the headlamps may also differ (e.g., U.S. or European low beams, motorcycle, bicycle). The beam pattern may also be different for other reasons, such as one headlamp not functioning, dirt or haze in the lens, voltage reduction, or misaim.

The most obvious and most frequent differences between passenger cars and trucks are differences in viewing angle, entrance angle, observation angle, and, sometimes, headlamp beam pattern. These variables can create a fairly complex set of interactions that have not yet been studied fully. We need additional data for better design of future lane-marking (and headlighting) systems.

The difference between U.S. and European beam patterns is one of the existing differences. For example, the European low beams, compared with the U.S. low beams, project only about one half the light in the direction of an edgemarking 100 m ahead. The importance of the beam pattern for visibility of pavement markings has been only superficially touched upon thus far, and should be studied further.

Motorcycles are very sensitive to changes in road geometry. While very little is known about the visibility of pavement markings by motorcyclists, motorcycles often have less than half of the roadway illumination when compared with drivers of passenger cars. Because of the high accident rates of motorcyclists, more research should be conducted to better understand their visual needs.

Bicycling is likely to increase in the future, but current bicycle lighting is poor. This presents a problem because bicycle paths often have unpredictable curves or other dangerous obstructions. Bicyclists have a need to see the route of the bicycle path because they are very sensitive to slight misjudgments. Because bicycle illumination is too weak to make the surface of the bicycle path visible, cyclists are in critical need of a high-performance lane-marking system.

4.15 Lane marking for special road-user categories

One of the primary goals of human factors is to design the environment to facilitate human activities. This principle should not only apply to typical road users, but to drivers with special visual needs as well. There are many groups of road users that might need support by improved or special lane markings (e.g., older drivers, tired drivers, visually impaired drivers, and drunk drivers). Furthermore, making lane markings better for these road-user groups would benefit all road users. However, few studies have been found that investigate visual requirements of special needs drivers under adverse conditions, such as rain or fog.

The role fatigue plays in accidents in night traffic is difficult to establish. Tired drivers are, however, a substantial problem for safety as they are overrepresented in single-vehicle accidents at night. Improved lane-marking systems may reduce this trend, but no studies have been found that address this problem, nor have there been any studies that investigate the effects of lane markings on drivers with degraded vision (except for older drivers).

4.16 New lane-marking concepts

There are few new developments in the lane-marking area. Profiled lane markings are fairly new in practice, but the technology has been around for more than ten years. Luminous raised pavement markers have been in use at most large airports for decades. In Sweden, experiments are in progress to use them in difficult and changing situations, such as car-ferry loading and unloading. In the U.K., a semi-intelligent luminous raised pavement marker has recently been introduced, primarily for temporary and difficult situations. It can sense road users and other conditions, and activates only when needed. Consequently, it does not have to be lighted all the time.

In Sweden and the U.S., studies are in progress to develop fluorescent pavement markings that would outperform standard markings not only in ultraviolet illumination, but also in incandescent illumination. Some promising preliminary results have been obtained already.

With retroreflective lane markings, illumination from a vehicle primarily benefits the driver of that vehicle. There is very limited help from other drivers. With fluorescent lane markings and ultraviolet headlighting, the markings become generally visible to everybody. Every driver helps other drivers in the scene to see the lane markings better. Another existing technology that has not yet been implemented

involves luminescent lane markings that are “charged” by each passing vehicle so that the markings becomes luminous for a certain period of time. This is an intriguing concept deserving further study.

4.17 Marking durability, maintenance, and costs

One of the primary practical problems facing pavement markings is how to increase their durability in a cost-effective way. Paint markings have low initial costs, but quickly lose their performance and require maintenance or replacement, costing money and time. Furthermore, the frequent maintenance repeatedly places workers in repeated dangerous situations. Raised pavement markings that have high photometric performance and heightened durability over long periods have been developed. They do not require repeated maintenance or frequent replacement, but have high initial costs. These two extremes involve large differences in cost and performance. What can be done to alleviate the need to trade one factor (cost) against the other (performance)? This is probably more a question for technical development of materials than for research on effectiveness of materials, but there are a number of research questions as well. For example: Could we replace line markings with raised pavement markings, or are these two types complementary? Is it better to have profiled line markings than to have flat lines complemented with raised pavement markers? Or is it better to have flat markings and replace them more often?

4.18 Development of a U.S. standard for photometric requirements

Most European countries have photometric performance requirements on pavement markings. The U.S. (at least at the federal level) is lagging behind. Concerted efforts should be made to rectify this void in requirements of pavement markings.

4.19 International harmonization of photometric testing and requirements

Europe is now in the process of developing a uniform photometric standard for pavement marking. However, before requirements are finalized, efforts should be made to find international consensus.

4.20 Conclusions

Lane markings for night traffic in use today do not meet acceptable levels of visibility and safety. Drivers need both long-range and short-range road guidance to be able to drive comfortably and safely. In many night-driving situations, present pavement markings do not provide sufficient long-range guidance. Either the pavement markings will have to be improved or the long-range visual guidance at night must be offered by some other road guidance system.

5. CONCLUSIONS AND RECOMMENDATIONS

The focus of this report was on the functioning of lane markings in night driving on dark roads. This section summarizes the main conclusions reached and offers proposals for future research.

5.1 The present situation and the need for improved lane markings at night

Section 2 concluded that drivers have a basic need for visual-guidance information in order to make accurate predictions about the future course of the road. Such enhanced knowledge should reduce uncertainty and errors in vehicle guidance.

Pavement markings enhance the configuration of the road and are likely used for both long-range and short-range road guidance. In daylight and in good-visibility conditions, drivers use lane markings for short-range guidance, and they are relied upon unconsciously and by means of peripheral vision. If lane markings are used for long-range guidance, they are probably used intermittently and by means of foveal vision.

Accident analyses show that pavement-marking systems have beneficial effects on accidents (see Section 2.3). These effects, however, are smaller than expected (on the average a few percent) except for combined marking systems, for which the effects are larger than expected (20 to 45%). There are a number of technical problems with some of these studies, such as combining day and night accidents.

Experienced drivers try to obtain long-range information about the course of the road to increase predictability. This is normally easy during the day, except for special situations such as fog, narrow curves, or intersections. However, during darkness, long-range scanning is often impossible. Drivers' ability to see the road when using low beams (the most common nighttime situation) is very limited; the visibility of the road surface is no more than about 30 m. This is insufficient considering normal speeds of 100 km/h.

Retroreflective lane markings or other retroreflective marking systems could play an important role, offering drivers road guidance far ahead of the vehicle. Luminous guidance systems are superior to retroreflective systems, but can seldom be used because of their prohibitive cost.

Studies have shown that the visibility of lane markings in difficult situations is approximately 60 m, about twice the visibility of the road itself. Lane markings with such limited visibility can primarily be used only with central vision and need to be processed consciously. Such processes make substantial demands on the driver's cognitive capacity, and can be used for short-range guidance only.

Both theoretical and empirical data indicate that drivers may use two complementary road-guidance functions—one for short-range and one for long-range guidance. When visibility for long-range guidance is reduced, drivers are forced to restrict themselves to the use of short-range guidance. The transition between these forms of guidance is determined by speed and other traffic variables. In general, however, the long-range guidance refers to distances greater than about 140 m, while the short-range guidance refers

to distances smaller than about 85 m. This is consistent with the estimate that drivers need about 5 s of preview time in order to be able to prepare for coming events (about 140 m at 100 km/h).

Another hypothesis is that drivers have two visual functions—one for guidance and one for recognition of objects. Studies show that both are degraded at night, but the performance of the recognition function tends to be impaired more. On the basis of this finding, some experts caution that if road guidance is substantially improved drivers may overdrive their recognition visibility and accidents may increase. There are studies indicating that this might happen in some situations. In the study most often cited (Kallberg, 1993), a road was equipped with side-post delineators (long-range visual guidance). On roads with relatively low geometric standards (but not for those with relatively high geometric standards) the average speed increased, as did the accident rates. It could be that guidance and recognition visibility should be improved together.

To draw the conclusion that road guidance at night should not be improved, however, would not be justified. Such a conclusion would suggest that we should not improve road guidance at night because it is better than object recognition at night. It is inconsistent with the results from studies of driver opinion, which indicate that better road guidance in night driving should be a high priority. It is also called into question by the overrepresentation of single-vehicle accidents in night traffic. Consequently, it is recommended that research and technical developments in the two areas—object recognition (and thus short-range guidance) and long-range guidance proceed in tandem.

5.2 Present standards and recommendations concerning lane markings

National and regional requirements on pavement-marking dimensions, colors, configurations, and meanings have existed for many years. Most of the major characteristics are approximately the same, but unfortunately there are still some important differences. There is also fairly wide agreement concerning the requirements for the materials used for pavement markings, but these requirements are not as well coordinated as for the dimensions and symbolic meaning of various lane-marking configurations.

The most recent standards concern photometric requirements. The brightness of pavement markings in daylight or within road-lighted areas have been measured for some time. However, not until recently has there been any systematic research on photometric requirements for nighttime retroreflective pavement markers. One problem has been the choice of the measuring geometry, involving a compromise between validity, flexibility, and reliability. The Europeans have taken the lead in this area. Their proposed standard measuring geometry corresponds to a driver in a passenger car (the driver eye height of 1.2 m, and the headlamp mounting height of 0.65 m) at a distance of 30 m from the markings.

The first step toward international harmonization should be to agree on a measuring standard. This would simplify comparisons between materials and between research results obtained in various studies. It is not clear whether the proposed European standard measuring geometry should be the one. That question could benefit from further research. For instance, the proposed geometry favors very short-range guidance and disfavors markings that are tailored to increase retroreflective performance at longer distances (long-

range guidance). There is validity to the argument that there should be more than one measuring point. Headlamps, for example, are not characterized by photometry at a single point. International cooperation in this area of research could prove to be very fruitful.

The present requirements seem to be a compromise between what is presently feasible (technically and practically) and what the drivers need. There is a fair consensus that the minimum photometric level for replacement of pavement markers should be 100 mcd/m²/lux, and that the preferred level for high classes of roads and markings be 300 to 400 mcd/m²/lux (using standard geometry). However, if these values of retroreflective performance are compared with the values needed to reach safe visibility distances (see Sections 3.5, 4.7, and 4.8), it is obvious that they are too low for even short-range guidance. It is no surprise that only a minority of drivers are satisfied with current lane markings. The performance of markers would need to be tripled to exceed the short-range guidance and reach minimally acceptable visibility for long-range guidance.

If it proves technically unfeasible to make traditional lane markings (lines) with such photometric performance, then it would be necessary to use alternative marking systems that can provide long-range guidance. Possible alternatives to supplement traditional lane markings are raised pavement markers and side-post delineators.

5.3 The need for further research on pavement markings

One of the main tasks of applied research in road safety is to offer a basis for improved decision making among various groups, including manufacturers, drivers, and governmental bodies.

In this section the research needs that have appeared in the previous text are briefly listed, along with the section(s) where that topic was treated in greater depth. Most of these proposals follow as a direct consequence of discussion in Section 4.

5.3.1 General research questions and topics concerning pavement markings

- What are drivers' road guidance needs in day and night traffic? (2.1, 4.2)
- Are there two separate functions for road guidance—short range and long range? (2, 4.3)
- When is short-range or long-range guidance used? (2, 4.3)
- Do the guidance functions work together or separately? (2, 4.3)
- Which criteria should be used to evaluate pavement markings? (4.1)
- What is the relationship between subjective and objective visibility? (3.5, 4.1)
- Do drivers need suprathreshold visibility within the visibility distance? (3.5, 4.4)
- What is the relationship between visibility and various behavioral measures (e.g., speed, lateral position)? (3.4, 3.5, 4.4)
- Study the changes of the coefficient of retroreflected luminance (R_L) in real geometry as a function of increasing the viewing distance. (3.2, 3.5, 4.6)

- Compare and test the validity of the models developed to calculate visibility of pavement markings. (3.5, 4.7)
- Establish regression equations and correlations between visibility and retroreflected luminance in a number of situations and for various detection percentiles. (3.5, 4.6)
- How can special-needs drivers (e.g., fatigued, old) be helped by modified lane markings? (2, 3.9, 4.15)

5.3.2 Specific research needs concerning lane markings

- Should lane-marking lines be complemented by some other system to offer drivers long-range guidance as well as short-range guidance? (2, 3.1, 3.3, 3.5, 3.7, 4.4, 4.5)
- How should pavement-marking systems be combined to achieve the best results? (2, 3.1, 3.3, 4.10)
- Compare the effects of changes in eye height and headlamp mounting height (passenger cars and trucks) on pavement-marking visibility and photometry. (3.2, 3.8, 4.14)
- Study the visibility of flat and profiled lane markings in various situations, with special emphasis on wet conditions. (3.3, 3.5, 3.7, 4.5)
- Compare the visibility and driver perception of traditional lines, profiled lines, and raised pavement markings in various situations, with special emphasis on wet conditions. (3.1, 3.4, 3.5, 4.12)
- Develop measuring methods, standards, and requirements for raised pavement markers. (3.1, 3.2, 3.5, 4.12)
- Study driver perception of lane markings on curves. (2, 3.4, 3.5, 4.13)
- Study driver use of lane markings in fog under day and night-driving conditions. (2, 3.5, 3.7, 4.5)
- Study lane-marking performance with frost. (3.2, 3.5, 3.7, 4.5)
- Study cyclists' needs for lane markings at night. (3.8, 4.15)
- Study the potential of luminescent pavement markings that are charged to be luminous for a period by the light from a passing vehicle. (3.1, 4.16)
- Perform research aiming at an international harmonization of photometric requirements for pavement markings. (3.2, 3.5, 3.6, 3.12, 4.8, 4.18, 4.19)

5.4 The need for further technical improvement

Technical development is normally based on research. Research here is used to indicate visibility or human factors research, not materials research.

5.4.1 General technical improvement needs

- The main technical development needs exist in the area of durability, maintenance, and cost. (3.5, 3.7, 3.11, 4.5, 4.11, 4.17).

5.4.2 Specific technical development needs

- Improved durability and performance of profiled lane markings. (3.5, 3.7, 4.5, 4.11, 4.17)
- Improved durability of raised pavement markers. (3.5, 3.7, 4.5, 4.12, 4.17)
- Development of pavement markings in which the coefficient of retroreflected luminance increases as the distance from the vehicle increases. (3.2, 3.5, 4.8, 4.19)
- Development of a portable and reliable retroreflectometer for field testing of raised pavement markers. (3.2, 3.5, 4.8, 4.19)
- Development of special lane markings for bicycle paths. (3.8, 4.14, 4.15)
- Development of lane markings that maintain their performance in frost. (3.7)
- Development of luminescent pavement markings. (3.1, 4.16)

5.5 Concluding comments

There is evidence that drivers make use of two separate, but complementary, road guidance functions—long-range and short-range guidance. Normally, both functions are used to create a complete representation of the roadway environment for proper road guidance. Long-range guidance is probably provided intermittently by central vision for prediction purposes, and short-range guidance is provided continuously by peripheral vision. But, in situations of degraded visibility, drivers are forced to rely on only short-range guidance (because the long-range guidance information is no longer available). When this happens, short-range guidance often has to be carried out centrally and intermittently.

Drivers' needs for nighttime visual guidance well ahead of the vehicle are still not fully met by the current marking practice. The visibility of lane markings in many nighttime situations is such that the markings can only be used for short-range guidance. Drivers fall back on this system because the primary system (long-range guidance) is not possible. Pavement markings offer much better road guidance than the road itself, but this is insufficient from the points of view of traffic safety and driver comfort.

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