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ADAPTIVE ILLUMINATION SYSTEMS FOR MOTOR VEHICLES: TOWARDS A MORE INTELLIGENT HEADLIGHTING SYSTEM

Kåre Rumar

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16. Abstract

Current vehicle illumination systems are facing a number of problems, including inadequate visibility and driver discomfort. One of the main reasons for these problems is that the current systems are static, and thus not responsive to changing conditions and situations. Recent technological developments such as new light sources, advanced optical engineering, and advanced electronics and sensors have made it possible to begin developing a new generation of vehicle illumination systems that would be adaptive to changing characteristics of the traffic, roadway, vehicle, weather, and lighting conditions in night traffic.

This study was designed to analyze the possibilities and limitations for designing a truly adaptive system. The report is speculative and optimistic in its nature. Several proposals are made, some based on research results, and some on personal experience and opinion. Consequently, this is not a traditional, formal research report. Rather, it is an effort to renew the discussion in an old area. Earlier efforts to design adaptive vehicle illumination systems are briefly reviewed.

The primary variables to which an illumination system should adapt are discussed. Ideas about how these variables can be measured in real traffic are put forward. An effort is made to estimate the magnitude of the advantage of adaptive systems mainly in terms of visibility. Also, possible obstacles and expected time frames for the introduction of such systems are discussed. Economic and technical limitations are not covered.

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Executive summary

Present vehicle illumination systems are facing a number of problems, such as inadequate visibility from a safety point of view and driver discomfort in night traffic. One of the main reasons for these problems is that the illumination systems are static. They do not change in relation to the varying road, traffic, vehicle, weather, and atmospheric conditions. However, technological developments have made it possible to start designing a new generation of vehicle illumination systems, a generation that is much more adaptive to the changing character of the traffic, the road, the vehicle, the weather, and the lighting situation in night traffic. An adaptive system may be built in one of two ways—a multicompartment headlight where the changing light is produced by various combinations of lighted compartments, or a changing single-compartment headlight. The ambition here is to suggest the latter—an adaptive vehicle illumination system with only two headlights per automobile.

This report is speculative and optimistic in its nature. Several proposals are made. Some are based on research results, others on experience and ideas. Consequently, it is not a traditional research report. Rather, it is an effort to initiate and renew the discussion in an old area, to start thinking along new lines, to see what possibilities and limitations there are to improve the present static, rather inefficient, and unintelligent vehicle illumination system.

The early parts of the report describe and analyze the present vehicle illumination systems. They are divided into direct (high beams, low beams, etc.) and indirect (side lights, under-carriage lights, etc.) illumination systems. The performance criteria to be used in evaluation of vehicle illumination systems are discussed. In rank order, they are: visibility, comfort, identification, distance and speed estimation, localization, and ease in handling.

The technological developments that have made possible this new approach to vehicle front lighting systems are discussed in terms of light sources, optical engineering, electronics, and sensors. Previous efforts to design adaptive vehicle illumination systems are reviewed. Comparatively few studies have been published.

The primary variables to which an adaptive headlighting system should be sensitive are discussed. Some limiting values for maximum and minimum intensity in various directions of a light distribution are suggested. The analysis is divided into four parts:

- Direct illumination in darkness and clear weather
- Direct illumination in darkness with fog or precipitation
- Front lighting systems in darkness with street lighting
- Front lighting systems for daylight conditions

Ideas about how the relevant variables can be measured in real traffic are put forward. An effort is made to estimate the expected magnitude of the advantages of adaptive systems in terms such as visibility and comfort. Also, possible obstacles and expected time horizons for the introduction of such systems are discussed. Economic and technical limitations are not considered.

The general conclusion is that the idea of a unified, adaptive, vehicle illumination system seems to be theoretically feasible. The main problems appear to be optical and practical, rather than electronic and theoretical. It is proposed that a system should be designed, so that it is possible to expand and upgrade in steps, depending on technological and optical developments and driver demands.

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1. Introduction

The present illumination systems for motor vehicles are static. That is to say they offer the same light distribution regardless of the conditions prevailing at the moment. This is not functionally ideal because the conditions in real traffic are almost always continuously changing. The road scene is changing, the traffic interaction with other road users is changing, the ambient light condition is changing, and weather and atmospheric conditions may be changing. Furthermore the change between different illumination functions (e.g., low and high beam) is stepwise (either/or), while the transition between the situations in which the various functions are supposed to be used is certainly continuous.

Over the years, numerous studies (from Johansson et al., 1963 to Sivak et al., 1992) have shown that the present vehicle illumination systems are not very good. In particular, the low beam system is not very good in terms of safety (detection distances, target identification, and target localization) and comfort (discomfort glare and feeling of insecurity). Consequently, there are strong arguments for improving vehicle lighting. One potential improvement could be to make vehicle illumination systems adaptable to the changing circumstances in night driving.

The term *adaptive* indicates that the vehicle lighting should change in response to traffic and to road conditions such as oncoming cars and road lighting. This includes, of course, the conventional front lighting systems such as high beam, low beam, fog lights, and spot lights. However it also includes other more unconventional lighting systems such as road border spot lights, side lights, and under-carriage lights (to be discussed later).

Lighting here means exclusively conventional lighting (incandescent, halogen, high-intensity discharge [HID]) and not lighting systems based on other concepts such as polarized or UV headlights. Non-lighting night visibility concepts such as radar and other short wave solutions will not be covered here.

For vehicle illumination systems, it is the reflected light that is of primary interest. The lamps and the light sources may not even be visible. On the other hand, for vehicle presence and signaling lights it is the lamp itself, and indirectly the light source, that are of primary interest. The lamp has to be clearly visible. Vehicle presence and signaling lights can, of course, also be made adaptive. That is probably an easier task than to make the illumination systems adaptive, because the interactions between vehicles are not as important and as complex for presence and signaling lights. But those lights will not be dealt with here.

At the first level of complexity, adaptive functions are characterized by one-way communications (e.g., steering-controlled light distribution in curves). However, the term adaptive does not exclude adaptive systems based on two-way communications (e.g., a platoon of cars adapting their lighting to each other). Such communicating illumination systems will be referred to as cooperative. Using these definitions and restrictions, one could consider two types of adaptive vehicle illumination systems:

(1) vehicle illumination systems that adapt to the road conditions (e.g., road geometry, markings, signs, and road surface reflection characteristics), the traffic situation (other road users), and one's own speed, and
(2) vehicle illumination systems that adapt to ambient illumination and atmospheric conditions (e.g., daylight level, street lighting quality, and fog density).

Proposals for making the vehicle road illumination systems dynamic and adaptable are not new (see Section 6 below). However, the fast development of information technology and its application in road traffic, together with the developments in the sensor area, optical engineering, and light-source technology have changed the situation and opened new possibilities. This new global situation is the main reason for reopening the discussion.

2. Problem

2.1 General problem

The general problem is to analyze road and traffic conditions to identify situations in which adaptive vehicle road illumination systems could enhance visibility, and thereby substantially improve safety and/or comfort for road users. Only systems that are feasible now or in the future using technology that is presently known, but not necessarily implemented, are considered. Efforts will be made to estimate size of the potential improvements, to outline how adaptation to situations and cooperation between vehicles could be achieved, to indicate the major obstacles for the introduction of such adaptive systems, and to estimate when the various adaptive systems could be implemented.

The main goal of this report is to discuss ways in which the present, static vehicle illumination systems could be improved by making them more dynamic—more adaptable to the ever changing road and traffic conditions. The idea is to make an outline of a unified adaptive headlighting system. A unified system, as compared with a complex, subdivided system with many lamps, would have many advantages such as lower costs, more reliable perception by other road users, and easier integration into the car body design.

2.2 Specific issues

(1) Determine the situations automobile front headlights could interact with or adapt to so that better visibility and/or higher comfort could be expected or reached:

- Other road users (including other headlights)
- Road geometry
- Vehicle parameters
- Ambient light conditions (including other light sources)
- Atmospheric conditions

(2) Estimate the magnitude of change in driver visibility and comfort that could be expected through adaptive vehicle illumination systems.

(3) Outline how the adaptation could be achieved, what type of data would be needed to allow adaptation, how such data could be obtained, and which type of lighting could be used.

(4) Outline the major obstacles for such adaptive vehicle illumination systems. Why do we not have them already?

(5) Discuss the specific interaction problems and possible solutions associated with vehicle illumination systems that adapt both to changes in the roadway, traffic, atmospheric conditions, and to ambient illumination levels.

(6) Estimate the likely time frame in which various types of adaptive vehicle-illumination systems could be implemented.

3. Present vehicle illumination systems

It seems logical to divide the current vehicle illumination systems into two major groups, differing in purpose and construction:

- Illumination systems that are mainly intended to improve the visibility conditions for the driver of the vehicle (e.g., normal headlights), to be referred to here as *direct illumination* systems.
- Illumination systems that are mainly intended to improve visibility conditions for other surrounding road users (e.g., side lights), to be referred to here as *indirect illumination* systems.

3.1 Direct illumination systems

The present direct illumination systems consist of two main headlight functions and some secondary headlight functions. The main ones are high beams and low beams. The secondary ones are front fog lights, front spot lights, curve lights, cornering lights, road border spot lights, etc. (see Figure 1).

Presently, each of these functions is static (or changing only marginally). There are some limited variations due to various car movements. There are a few headlight systems that are truly dynamic, such as curve headlights that are controlled by the steering wheel and other inputs (for example speed and the use of direction indicators). The curve lamps are intended to facilitate driver visibility conditions in curves. But most headlight functions are truly static. This is not ideal since the conditions in which they are used are often changing.

Engineers have put considerable effort into eliminating some of the unwanted variation of the illuminating systems. There are many descriptions in the literature of headlight leveling devices. Most leveling devices are intended to counteract the variation of headlight aiming that is caused by changes in vehicle loading. There is, however, no known corresponding interest in creating a change where it could be advantageous (for example upwards aiming at driving in depressions). One of the reasons for this may be that the regulations concerning headlights are, in principle, constructive and static (not functional and dynamic). This regulation rigidity limits development that could improve visibility. U.S. Department of Transportation in fact proposed the introduction of functional low-beam regulations in the 1980s. The proposal was, however, never implemented.

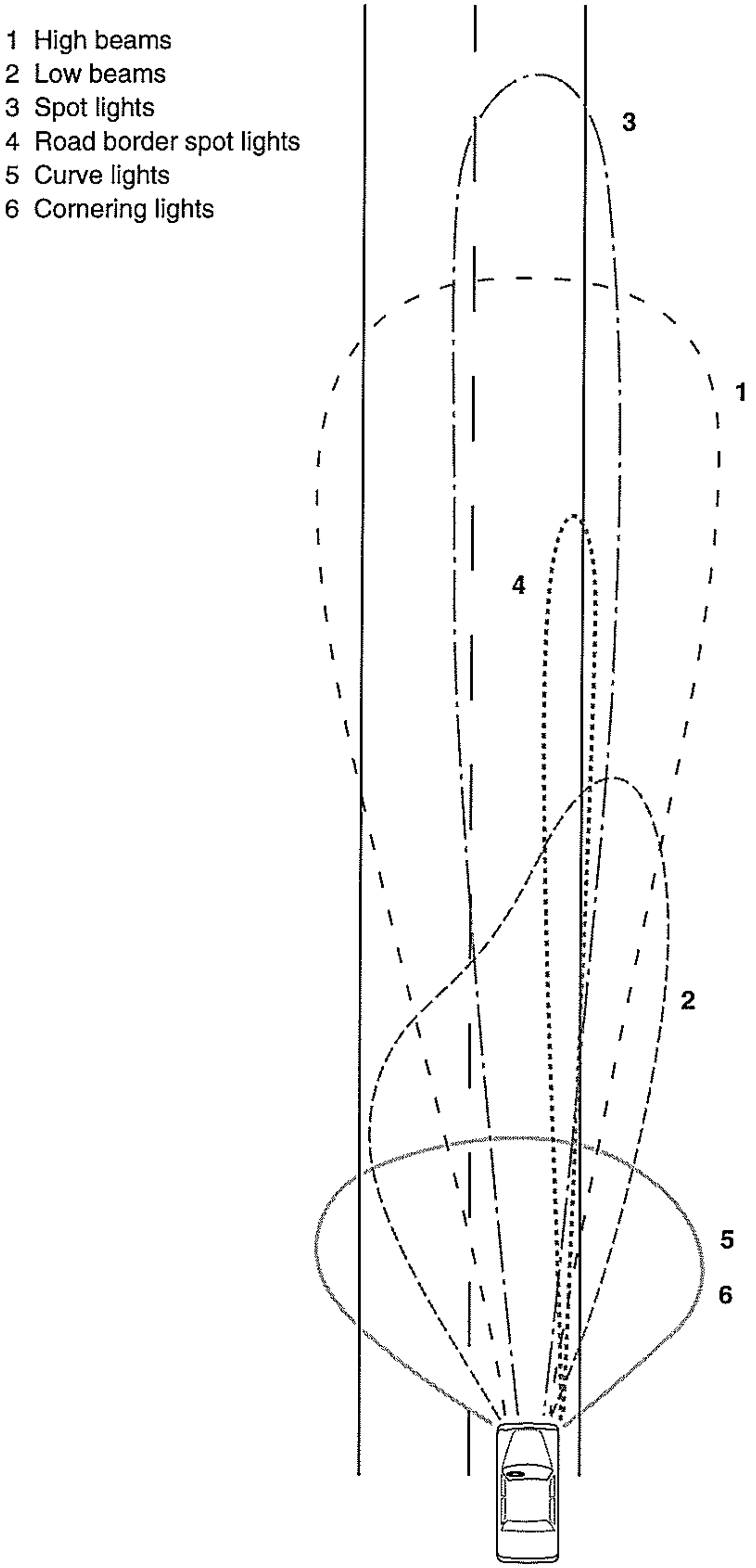

Figure 1. Direct vehicle illumination systems.

3.1.1 High beam

Although the design and regulation of the present high beam light distribution is no major problem, it is still obvious that driver visibility could be improved if the distribution were changed in several ways. For example, it would be beneficial if the beam intensity could be narrowed on flat and straight roads at high speeds, and widened on curved roads at lower speeds. The present light distribution is not adapted to the road. That is to say, specific illumination is not directed towards particular objects of interest, such as road delineation and traffic signs. More light above the horizontal could be an advantage in areas where overhead signs are frequent, but it could be a disadvantage in situations with fog. In snow, much light close to the vehicle is generally undesirable, because it creates a glare source for the driver and it raises his adaptation level unnecessarily. The process of switching from high to low beams could most probably be made both safer and more comfortable in a more dynamic way. It would thereby not cause the present abrupt change for both the driver of the vehicle and for the oncoming drivers.

The mounting height of the high beam is also of interest. In some countries the roads in winter are lined by high walls of plowed snow. For such conditions the lamps should be placed higher to see what is coming from behind the walls (e.g., a child, a moose, a reindeer). This is of more importance the higher up in the vehicle the driver is sitting. High-positioned high beams therefore have become of interest to truck drivers. High-positioned high beams give an early signal to the oncoming driver (for better or worse) to switch off his high beams.

3.1.2 Low beam

The main problem in vehicle front lighting is, however, the low beam. The present static low beam is based on an impossible contradiction—to have good illumination of the scene in front of the driver without causing glare to the oncoming drivers. One crucial characteristic of front low beam illumination is, therefore, the relation (ratio) between illumination below and glare above the cutoff in each horizontal direction of the low beam light distribution. Especially for retroreflective targets, however, the absolute illumination values rather than the relative values are important (Padmos & Alferdinck 1988). Another parameter is the gradient in, and the form of, the cutoff region that will influence the sensitivity to aiming and the possibility of aiming visually. A third important parameter is the illumination well above the horizontal in the direction of overhead road signs. A fourth property is the amount of light well below the horizontal and wide to the sides for orientation of the driver on the road. A fifth relevant area is the road straight ahead, at near distances, contributing to self glare and adaptation.

Several studies indicate that visibility improvements are to be expected if the light above the horizontal is increased. Such an improvement will then be reached at the expense of increased discomfort glare.

The largest potential for improvement of the low beam light distribution is easy to specify in general terms: less glare towards the oncoming driver and more light towards the relevant targets. For the static low beam, there are only very limited possibilities for further improvement along these lines. However, for adaptive headlights, substantial improvements are possible.

3.1.3 Secondary direct illumination systems

The secondary direct illumination systems mentioned above and illustrated in Figure 1 have light distribution parameters and problems corresponding to the high and low beam systems, depending on whether they are intended to be used together with the high beam, together with low beam (to improve the visibility situation for the driver), or as a replacement for the low beam in specific situations.

3.2 Indirect illumination systems

The indirect illumination systems are primarily intended to improve visibility conditions for other surrounding road users. There are presently no indirect illumination systems on the market; no vehicle illumination system available is constructed primarily to improve visibility conditions for road users outside the vehicle in question. On the other hand, most direct illumination systems fulfill this purpose to some degree. All headlighting systems not only illuminate the road scene for the drivers, but they also illuminate the road, the road signs, the road markings, etc., for other road users. That is, however, not their primary function.

During the development of vehicle illumination systems, however, such specific indirect illumination systems have been proposed several times. A system may have been proposed but not caught enough interest, or it may have been forgotten and some years later proposed again in the same or in another country. For the side light (see Section 3.2.1) this has been repeated several times.

A general problem with the indirect systems is that the drivers themselves receive no benefit from them. They are exclusively intended for the others. Consequently, there are only costs, no incentives for the user. Also there is no incentive for the manufacturer to equip the vehicle with such a system. If indirect illumination systems are supposed to play a substantial role in night traffic, their use must be widespread. However, the only way to gain widespread usage is to make them compulsory by legislation. This has never been done for indirect illumination systems. But it is exactly what has been done for presence and signaling lights, which are also intended for other road users. Thus, it can be done.

Examples of the indirect vehicle illumination systems are side lights, under-carriage lights, top lights, and possibly road-marking lights (see Figure 2).

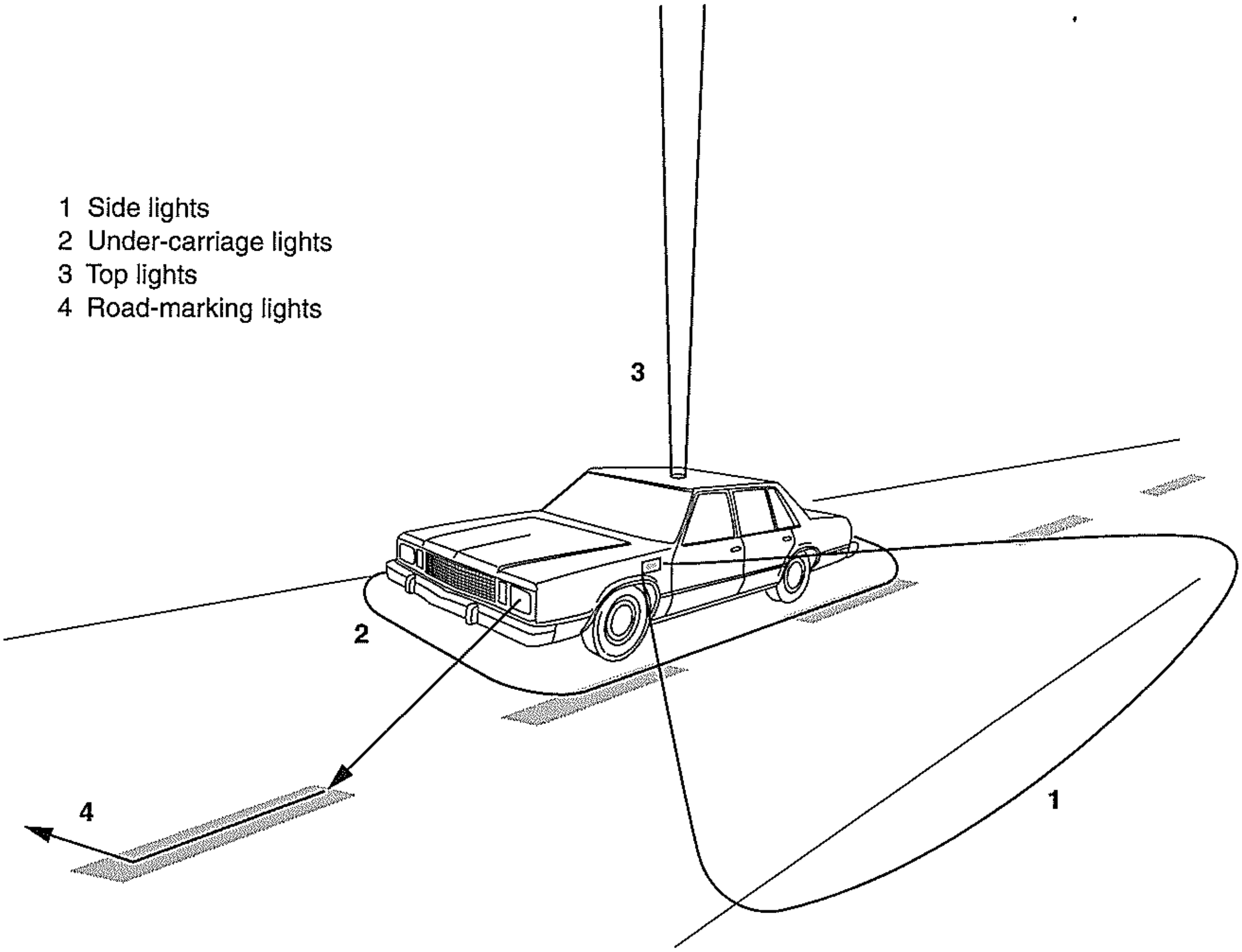

Figure 2. Indirect vehicle illumination systems.

3.2.1 Side lights

One type of indirect illumination system is the side light (Sims, 1928; Allen, 1962) or courtesy light (Wilkenson, 1973). (Side *marker* lights on the other hand are really presence lights and not an illumination system.) The side light was, in fact, on the market at one time. This lamp is intended to illuminate the opposite lane beside the car so that the oncoming driver can see obstacles on his lane far beyond the range of his low beam system (see Figure 2). Obstacles may be detected in direct illumination from the side lights or they may be detected as silhouettes against the bright road surface illuminated by the side lights. If several cars in an oncoming platoon have these side lights the effect is, of course, enhanced.

3.2.2 Under-carriage lighting

Another indirect illumination system that exists, but is very unusual, is the under-carriage illumination system (Wördenweber, 1996). This illumination system is placed under the car and illuminates the road under the car, thereby creating a bright surface which is moving with the car. Such an illumination system is likely to facilitate the perception by other drivers of the relative movement of the car, especially in the lateral direction. It represents an effort to reproduce the stimuli that are present in daytime traffic when the car's motion in relation to the road surface and the road markings is a useful cue.

The under-carriage illumination system could also allow the other road users to make better estimates of the distance to and speed of the car in question. We know that shadows are important cues for three dimensional vision in daylight. In darkness, on roads without fixed overhead lighting, shadows are not present. The under-carriage illumination could create an inverted shadow, which at night could play the same role that the ordinary shadow does in daylight—to improve the ability of the other road users to interpret the scene in front of them.

3.2.3 Top lights

One of the few advantages in night traffic relative to daytime traffic is that it is possible to perceive the presence of an approaching car, because of the light it emits, before the car itself is visible (e.g., in curves, on hill crests, at intersections). As soon as there are some areas that can reflect light from the headlights of the other car, its presence is perceived and sometimes its location is fairly well estimated. These reflective surfaces may be the road itself, telephone poles, trees, buildings, particles in the atmosphere, etc.

In most populated areas, the air is dirty enough to make the light from other vehicles visible in the atmosphere. This is the basis for a proposal that cars should have narrow top lights on the roof aimed vertically upwards. Thereby, a vertical pencil of light would make cars visible at large distances, long before they became directly visible. By such an indirect illumination, the position and the speed of the other vehicles could also be fairly well estimated before the vehicles themselves become visible. This would most probably improve driver prediction of what will happen in the immediate future. This could be important from both safety and comfort. It is hard to see any drawbacks of such a light except for the added energy consumption.

3.2.4 Road-marking lights

Several proposals have been made to announce the approach of an oncoming vehicle before it becomes directly visible, by illuminating the road, the road markings, or the side post delineators well in front of the vehicle. The length of the illuminated section of road could be adapted to conditions such as speed of the vehicle, coefficient of friction, size of the vehicle, etc. (See, for example, Aono, 1990.)

Several technical solutions are offered. The lights of the vehicle may be sensed by photocells that will influence light-emitting diodes in the road, the road markings, or the side-post delineators further on. The light from the car may be picked up by optical fibers and directly transferred to a road marking further ahead. Other more electronic solutions, are, of course, possible.

4. General problems associated with the evaluation of vehicle illumination systems

4.1 Visual performance

Night traffic is characterized by two important conditions that have a major influence on visual performance:

- The prevailing illumination levels are substantially lower than during daylight conditions. Still, the luminance levels that are typical in night driving are high enough that the visual task can be performed with the cone receptors of the retina, rather than the rod receptors. Although it is called "night" driving, the task involves primarily day vision (i.e., photopic vision, or perhaps mesopic vision). The contrast sensitivity in the central part of the human eye is low at those levels of illumination. High contrasts are therefore necessary to exceed the visual threshold for detection.
- The differences that exist between dark, badly illuminated areas and bright, glaring points such as oncoming headlamps are very high. It follows then, that high levels of veiling glare in the eyes will often further reduce the already low contrast sensitivity.

Both of these conditions influence visual performance as well as visual comfort. Those effects vary considerably among individuals. The evaluation of various proposals for adaptive lighting will have to be based on reactions from road users (primarily drivers) in response to various aspects of the systems. From a performance point of view, the task of the vehicle illumination systems is to keep illumination levels and visual-field contrasts high, and glare low. These are very difficult requirements to reach, especially in real traffic.

4.2 Criteria

The first problem is to determine which criteria, or dependent variables, should be employed. It seems rational to choose driver visibility (which is most relevant from a safety point of view) as the primary criterion, followed by comfort. What are the other criteria and how should they be weighted in relation to visibility?

Traditionally, visibility has been the number one criterion. However, recent trends in automobile design seem to indicate that this is not always true. If the difference in visibility between two systems is small, then the comfort value is important. The likely reason for this is that the consumers are rarely able to perceive and estimate visibility accurately, while they certainly can continuously perceive and estimate visual comfort. However, if the visibility difference between two systems is sizable, then the comfort value is considered secondary.

Glare is an illustrative example of this problem. Glare has two effects. One, which is often called disability glare, is objective and directly influences visibility mainly by causing measurable stray light in the optic media. The other, which is often called discomfort glare, has a subjective character, and causes, as the name indicates, discomfort. These two aspects of glare are, of course, related to each other. Expressed in a simplified way, one can say that in actual traffic, with oncoming vehicles equipped with the present headlights, there is only one way to gain longer detection distances, and that is by accepting increased glare. It is normally not possible to have both good visibility and low glare. However, adaptive headlights (and polarized headlights, and UV headlights) could offer solutions. In Europe, relatively more emphasis is placed on driver comfort, and glare levels are not allowed to exceed relatively strict values, even if that would enhance visibility.

There is also a third criterion, namely identification or recognition. It is not always enough to detect that there is a target ahead. In order to decide what to do, drivers also have to identify what kind of target it is. Often a luminous point source is detected (for example, a piece of retroreflective material). But is it part of a side-post delineator, a mail box marking, a bicycle, a pedestrian, or the glowing eye of an animal? Identification is, however, outside of the scope of this discussion, because most of the solutions for this problem lie with the target, not the lighting system. (See e.g., Luoma, et al., 1995.)

A fourth criterion might be localization. For point sources of the kind that are so common in night traffic, it is often very hard to make an accurate localization. Just where is the target positioned? Again, the solution to this problem most often lies in the target and not in the illumination. However, for activity illuminated targets the design of the illumination can probably be of considerable help (e.g., under-carriage illumination - see Section 3.2.2).

Analogous problems with distance estimation may occur with silhouettes. As we often cannot see the bottom part of the target, its position is not anchored and it is difficult to estimate its distance. Here, vehicle road illumination, especially on the oncoming vehicle, may facilitate the task of the driver.

4.2.1 Visibility

Given that visibility is our number one criterion, there still are a number of open questions. What kind of visibility are we talking about?

- Detection distance or identification distance?
- Average visibility or minimum visibility?
- Typical targets or difficult targets?
- Targets in front, to the right, or to the left?

- Subjective visibility or objective visibility?
- Visibility under ideal conditions or under the full range of real conditions?

My view is that in most cases we should evaluate vehicle illumination systems based on

- Minimum detection distance (not the absolute minimum but, for example, the 10th percentile)
- Typical difficult targets (critical targets that are common on the road for which the lighting is intended)
- Targets situated anywhere on the road
- Objective visibility (although Neumann & Stoll, 1996, found that drivers have a fairly good idea about the quality of the headlight just from looking at the light distribution)
- Studies in actual traffic situations (although, if done carefully, this might very well be simulated on closed courses)

4.2.2 Comfort

Several issues concerning comfort (or discomfort) need to be addressed:

- How do we measure comfort (see Weintraub et al., 1991)
- Which comfort level should we use? Should it be the mean, the median, the 90th percentile or some other value?
- How do we weight comfort against detection distance?

The most widely used discomfort glare index is the classic de Boer index (1967) or newer versions of it (e.g., Sivak et al., 1990; Theeuwes & Alferdinck 1996). The question of which glare value should be used is almost impossible to answer in a simple way. It all depends on the situation. Discomfort glare is very sensitive to anchoring and range effects. It is suggested not to use the median or the mean, but to take into consideration some of the more extreme discomfort values and to use, for example, the 75th percentile on the discomfort side. As indicated earlier, comfort enters into consideration mainly if the differences between the detection distances are not too big. There are simulation models that assign weights to the various criteria (including visibility and comfort) and combine them in an overall figure of merit (e.g., Bhise, 1984).

4.2.3 Other criteria

Identification is left out of this discussion because it lies, to a large extent, with the target itself. Localization is of some interest here, especially for indirect vehicle road illumination systems and, of course, for the positioning of the light sources on the front of the vehicle.

The distance between the headlights (or rear lights) has a clear effect on perceived distance of oncoming cars (Flannagan et al., 1995). Thus, it is the ambition in this report to suggest a lighting system that integrates the adaptive functions into *one* headlight (on each side of the front of the car). Thereby, the distance between the headlights can be fairly well standardized, which will facilitate distance estimation for other road users.

A criterion which is of a somewhat different character is the driver task in handling the illumination systems. Currently, it is often difficult already to detect whether the oncoming car is driving on high beams or on low beams that are misaimed, or appear more intense than normal because of vertical or horizontal curves. Because this condition is a prerequisite for handling the system (dipping or turning off the high beams), it complicates the task of the driver.

An efficient automatic adaptive system would relieve the driver of this task. If, on the other hand, the system is only semiautomatic, that is, if the driver has to initiate the changes, then the task is probably even more difficult with an adaptive system than with the old systems, which have comparatively clear differences between modes. The change in the driver task has to be weighed into the evaluation of the adaptive illumination systems.

4.3 General conditions

To design and build the optical system of a headlamp or a headlamp system that can offer the desired light intensities and control the glare in the directions required is difficult in static situations and very challenging in dynamic situations. However, this is mainly an optical engineering problem. Furthermore, it has to be solved with a comparatively inexpensive technology. The difficult optical-engineering, quality-control, and production problems involved in implementing adaptive lighting systems will not be treated here.

Another problem is to design a system in which several dynamic and cooperative low beam systems can cooperate without impairing each other's functioning. This may be a major problem since the various adaptive systems may have contradictory, or at least conflicting, requirements. In such situations, some kind of a hierarchy must be constructed. These potential problems will be touched upon but not treated in depth.

An additional problem is that if adaptive lighting systems are introduced, there will most certainly be a long transition period before all vehicles have them. The adaptive systems must work in relation to other adaptive systems, but they must also work together with traditional lighting systems without reducing the visibility and comfort or increasing the handling problems for the drivers of those older cars.

A general problem in automobile lighting, as well as in most other areas of construction and usage of daily-life equipment, is the gap between the ideal design and the real-life equipment that is in the hand of the operators. A lamp looks one way and gives one light distribution on the drawing board and in the testing laboratory when it is new and clean, has accurate voltage, is correctly aimed, and is handled as intended. It often looks very different and gives a different light distribution in real traffic when it has been used for a couple of years, is dirty and degraded, not accurately aimed, has a voltage drop, and is controlled in a way that was not intended. The more accurately the light distribution is designed, the more detrimental are many of the deteriorations. For instance, if we have an adaptive light distribution of some kind, then it is essential that the headlamp remain efficiently cleaned. The problem of real traffic conditions must be treated in connection with adaptive vehicle illumination systems.

Finally, the standardization of the adaptive vehicle road illumination lamps will have to be considered. Results from high-beam studies (Helmers & Rumar, 1975) show that an important factor in night traffic is the equality or the ratio between the intensities of two or more oncoming headlights. When the intensities of two oncoming high beams are equal, visibility distances to dark obstacles are about the same, even when the absolute intensity of the two high beams is varied over a wide range (about 10 times). On the other hand visibility is seriously impaired for the driver who has a car with considerably lower high-beam intensity.

Therefore, it is not enough to specify the light distributions in relative terms. The adaptive lights will have to work on the same absolute levels. Either this must be specified in the regulations or standards, or the lamps will have to be designed in such a way that the adaptive process itself leads to such a situation.

Somewhat contrary to the above are the results of Flannagan et al. (1996) on visibility distances with low beams of different intensities. Their results differ from the above, since they found that an intensity increase of 3.8 times of both one's own and opposing low beams resulted in a visibility improvement of 17 percent. There are, however, a number of differences between these two studies that could account for the different results of Helmers & Rumar (1975) and Flannagan et al. (1996).

5. Technological development

As was indicated earlier, one of the main reasons for raising the question of adaptive vehicle lighting now is that numerous technological developments have taken place during the last decade. Below are listed the main trends and developments, without going into technical details. To facilitate the description, the field is divided up into four parts:

- Light sources
- Optical engineering
- Electronics and ITS (Intelligent Transportation Systems)
- Sensors

5.1 Light sources

Light sources have progressed from the initial kerosene lamps to acetylene lamps, to carbon arc lamps, and then to incandescent lamps with initially one and later two filaments. In the sixties, the incandescent lamps in Europe were replaced by the halogen lamps, which had close to three times the flux of the incandescent lamps. First came the H1, H2, and H3 lamps, later the H4, and now the H7 lamps, all with successively better performance.

In the nineties, the HID (high-intensity discharge) lamps were introduced on the market. These have about two times the flux of the halogen lamps. They have, furthermore, longer life, higher color temperature, and a more concentrated light source.

On the other hand, the HID lamps require higher voltage to start and to burn. Their color rendering is somewhat different from incandescent lamps, and they require better control of the light distribution. They are also considerably more expensive.

Results from visibility studies indicate that the visibility advantages of using light sources with higher flux are rather modest. On low beams, for example, the halogen bulb only improved visibility by about ten percent (Rumar, 1974) in spite of a three-times higher luminous flux. On high beam, on the other hand, nine-times-stronger beams gave a 74 percent improvement of visibility. For the low beam, the limiting factor is, to a large extent the regulation, which is very strict on amount of glare above the cut-off. This is especially the case for European low beams. For the high beam it is rather the inverse square law of illumination that gives a gradually reduced advantage of stronger light sources.

There are many alternative light sources developed for signal lights (e.g., light-emitting diodes and neon) but as far as is known, there are no other light sources developed for headlighting purposes. There is, however, a possibility that microwave light sources may be an interesting type of lamp in the future. With modern semiconductor technology it is now possible to produce small, inexpensive, and efficient microwave magnetrons. The cost, the lifetime, and the possibility to select wavelength of the emitted light are very competitive. Further development is required.

5.2 Optical engineering

Substantial progress has occurred in the field of optical engineering. The main developments are:

- Projection technology (projector headlamps)
- Light distribution technology (free-form reflectors and accurate prisms)
- Distributive lighting technology (high-intensity light sources distributing light to headlights by means of optical fibers)

Within projection technology, it is now much easier to distribute light in the desired directions without producing stray light in other directions. Some of the more important developments are:

- The projection lamp makes it easy to change the light distribution.
- The tailor-made (free-form) reflectors (discrete or continuous) make it possible to effectively use the whole reflector, even for low beams.
- Inner lenses with more detailed and accurate prisms of glass or plastic make possible more accurate light distributions.

These improvements have made it possible to get the same amount of light, and an even better light distribution, out of much smaller headlamps than were previously possible. However, this tempts the vehicle manufacturer to equip the car with smaller headlights. And using the same technology, a small headlamp is always less efficient than a large headlamp. Furthermore, a smaller headlamp normally has a higher luminance (and is perceived to be more glaring) than a large headlamp (Sivak, Simmons, & Flannagan, 1990).

Another use of improved optical engineering is that the adaptive functions of a front lighting system can be achieved by using multicompartment headlights, where the changing light distribution is produced by a combination of lighted compartments. Such an adaptive procedure is discrete rather than dynamic. In my opinion, it is a step towards a fully adaptive system. It is suitable, for instance, for having different light distributions for different roads and other clear cut situations. This seems to be the way the Eureka Advanced Frontlighting System (see Section 6.1) intends to go. But it is not truly adaptive to finer changes in the driving situation.

The projection technology offers possibilities to modify the light distribution of a headlamp in a fairly simple way. So far, it has mainly been used for static purposes. But there does not seem to be any principal obstacle that prevents this technology from being used for dynamic changes of the light distribution. In other words, projection technology seems to be a method suitable for producing truly adaptive front lighting systems (see Lucas Autosensa, Section 6.2.1).

Distributive lighting technology can offer more light at a lower cost than conventional headlamps. The differences can be large. As an example, Jenkins et al. (1996) indicate that 50 percent more luminous flux can be achieved using 35 percent less power. Because the light source can be placed elsewhere, this technology also has substantial advantages from a styling point of view, a view that has an unfortunately large importance in the design of headlights. Styling considerations have often proved to be counterproductive for driver visibility. The area and the volume allowed for the headlights on a car have been steadily decreased by the automobile manufacturers (Neumann, 1990). An adaptive headlight could solve some of these problems if it could be integrated into one lamp. If, on the other hand, an adaptive system would require a large number of lamps to fulfill its purposes, the opposition from the automobile manufacturers is likely to be strong.

Another way to use fiber optics to produce an adaptive front lighting system could be to equip each bundle of fibers with a lens and direct the light in a specific direction. The adaptive function could then be achieved by turning on and off a specific combination of optical fiber bundles. A critical question is what kind of light efficiency such a reflector-free adaptive headlight would have.

Not really belonging to optical engineering, but somewhat related, are dynamically leveling headlights. Present headlights can be adjusted vertically (manually or automatically) in order to compensate for changes in aiming brought about by changes in vehicle load. This ability to adjust the aiming of the headlights could, of course, be used for other purposes. The first leveling devices that are quick enough to compensate for the vehicle motions brought about by acceleration or deceleration have just appeared. Such devices are, in fact, adaptive in the sense used here. Some headlights are also moveable in the horizontal direction (e.g., special curve lights). These types of headlights are also adaptive.

5.3 Electronics and ITS systems

Several types of adaptive functions for vehicle illumination systems (e.g., dynamic leveling and active curve lamps) will require sensors to signal changes, a relatively simple computer to process the signals, and probably an electric device to carry out the motion. In the future, such specific systems will likely become frequent.

The concept of making traffic more intelligent has been brought up several times since the start of motorization. Traffic lights have for a long time been controlled by computers. However, it has been only quite recently that processors have become sufficiently small, inexpensive, and powerful to play an important role in the control of cars. Another development that has taken place within ITS is the utilization of communication channels with varying wavelength between the vehicle and the surrounding road environment.

The ITS technology is intended to help the driver in many ways. It is customary to distinguish three main types of use:

- Informing the driver (e.g., about congestion ahead and alternative routes)
- Assisting the driver (e.g., in making a lane change)
- Taking over from the driver (e.g., braking in an emergency situation)

These three levels of technological applications are relevant also in connection with adaptive vehicle illumination systems.

Through ITS systems it is now possible to know the instantaneous relation in space among vehicles in actual traffic. It is also possible to know the status of various controls (e.g., brakes applied, low beam or high beam in use, direction indicator activated). This is, of course, very important for adaptive vehicle illumination. These data may be used to control the front light distribution of cars involved in oncoming situations as well as in following situations.

5.4 Sensors

In general, current sensors are smaller, less expensive, and more powerful than just ten years ago. That is true also for photometric sensors.

Sensors will be crucial in the development of adaptive vehicle illumination systems. Comparatively simple sensors will be used for adaptive systems such as leveling devices. A more complex set of sensors from which signals are processed and compared will be necessary for more advanced adaptive functions, such as modifying the glare against the oncoming drivers.

Current prototype ITS systems make extensive use of sensors to register the relations between vehicles. Most of the conditions relevant for adaptive lighting may therefore be already monitored by existing sensors. However, some conditions of relevance for adaptive lighting are not intended to be sensed and processed in the ITS world. Therefore, sensors that can report on such conditions might have to be developed separately for the present applications. Sensors that belong to this category are, naturally, mainly light sensitive. It is, however, important that such sensors are included in, and integrated with, the total architecture of the ITS systems so that they do not become a separate family that has to be adapted to ITS systems afterwards.

6. Previous efforts to develop adaptive vehicle illumination systems

A literature survey revealed that very little has been published in this field. One of the reasons is probably that adaptive illumination is potentially a competitive feature among future automobile models. Therefore, individual companies have likely tested the feasibility of adaptive vehicle illumination systems, but, for competitive reasons they have not published many of these efforts. However, as was stated earlier, recent development of information technology, new light sources, and advances in optical engineering have renewed the interest in recent years. At least two different international conferences during 1997 have put adaptive vehicle lighting on their programs (Society of Automotive Engineers, Detroit, U.S.A., February 1997; Progress in Automobile Lighting, Darmstadt, Germany, September 1997).

6.1 The EUREKA project AFS

The most recent project concerning adaptive vehicle illumination systems is the European EUREKA project AFS (Advanced Frontlighting Systems). The project (AFS, 1994) has just passed the initial feasibility-and-analysis phase of its planned six years (AFS, 1996). It started in early 1994 and is planned to end in early 2000. The next two-year phase will involve field tests. Finally, a draft new-vehicle headlight regulation is scheduled to be presented in 2000. The plans are presently classified, so it is difficult to find out what is really going on. What follows is the information that is publicly known today.

The clearly stated main objective of the project is to come up with a new proposal for an international or at least European vehicle lighting regulation for the next century. The ambition is to improve traffic safety, driver comfort, and reduce power consumption.

The current project plan specifies advanced front lighting for six specific situations:

- Bending light (curves)
- Adverse weather (wet road surfaces, rain, snowfall, fog)
- Motorways (divided, high speeds, large radii)
- Overhead sign lighting
- Country lighting (rural)
- Town lighting (street lighting, unprotected road users, and intersections)

The four initial situations have been analyzed, while the last two situations have not yet been treated.

The goal is to move from design (construction) regulations to functional regulations, to come up with a front lighting system that is able to adapt to the varying conditions in night driving. It currently deals with low beams only, but the intention is that it will also include high beams, fog lights, etc. Presently the project is financed by twelve European car and lighting equipment manufacturers. A market analysis shows that there is a substantial interest in an improved low beam system. The industrial consortium has applied for financial support from the European Union for the upcoming expensive field evaluations.

The AFS project has several similarities to the goal of the present report. However, it is also different from the present project in several ways. The AFS project has a clear intention to establish optimal light distributions for some specific situations and to regulate them. The present report has no ambition to optimize the light distributions for various situations, but rather to discuss in more general terms the advantages and disadvantages of various strategies and designs. AFS is limited to using technology presently on the market. For example, it seems to be the intention of AFS to mainly work with discrete changes of light distribution based on multicompartment headlamps where different combinations of compartments are lit to achieve the different light distributions. This report will also consider technology that has yet to be developed, and is aiming for a single compartment headlamp in which the light distribution may be dynamically and continuously changed.

6.2 Studies of specific adaptive vehicle illumination systems

In this section a number of specialized adaptive systems will be reviewed.

6.2.1 Lucas Autosensa

The Lucas Autosensa (Jones & Hicks, 1970) was probably the first advanced (cooperative) adaptive headlight system built in a prototype series. It was tested with good results but for some reason never put in production.

The goal was to have a supplementary low beam that would adjust its aiming automatically (depending on the position of the oncoming car), in order to minimize the glare in the direction of the oncoming driver. It consisted of a projector lamp with a moveable aperture that could change the side (vertical) cutoff of the light distribution. This shutter was governed by a receiver unit sensing the angular position of the oncoming car. This way the glare towards the oncoming driver could be considerably reduced. The system was intended primarily for rural, high-speed, open roads.

The visibility improvements achieved were considerable. With a separation of 7.6 m between the courses of oncoming vehicles, the visibility was estimated to increase from near 50 m with standard low beams to above 75 m with the supplementary Lucas Autosensa. Reported problems included driving in built-up areas, on curvy roads, and driving in convoys.

6.2.2 Leveling devices

As has been mentioned several times above, the leveling devices that have been around for a couple of decades are also a type of adaptive system. The traditional purpose has been to compensate for changes in headlight aiming caused by changes in the load of the car. The initial devices did not really have the sensitivity nor the precision necessary to achieve their purpose. In order to work well, aiming has to be adjusted with very high precision, which is an ambitious task in the tough real-world environment, and at the relatively low cost needed for automobiles. The first designs were controlled by the driver using a limited number of steps depending on the load characteristics. Later designs are fully automatic and continuous. More recent constructions are quite advanced and are able to reach the resolution required. They are even so fast that they can react to changes in the aim caused by acceleration and deceleration.

Of course, the visibility gains due to leveling devices vary with the character and the amount of misaim. Since the headlights are normally aimed with only the driver or nobody in the car, the aiming problems are often that the headlights are aimed too high. Consequently only the oncoming driver suffers. His/her visibility may, in some more extreme cases, be seriously decreased due to excessive glare. On the other hand many drivers and repair shops intentionally aim the low beams too low in order to avoid such problems. Aiming too low seems to be a larger safety problem than aiming too high (Cobb, 1990). There is an obvious feedback for aiming too high (flashing from oncoming drivers) but no feed back for aiming too low. This tends to make aiming too low more frequent.

The European low beam with its very sharp cutoff is, in most normal cases, relatively insensitive to glare, due to its abundance of light below the sharp cutoff. Therefore the typical visibility improvement due to reduced glare with leveling devices for European low beams is approximately ten percent (Rumar, 1968). On the other hand the European low beam is, for the same reason, more sensitive to misaim than U.S. low beam (Sivak et al., 1994).

6.2.3 Gradual dipping of the high beam

In the beginning of the seventies a Swedish inventor (O. Wilje) came up with the idea that when switching from high beam to low beam, the high beam should gradually fade away over a period of about ten seconds, instead of an abrupt switch from one beam to another. As has been indicated earlier, this is consistent with the gradual change in distance between oncoming cars. Consequently, the system proposed was adaptive. But it was only adaptive in an ideal situation (encounter on a flat straight road), not in real-life conditions where car encounters take place on roads with a variety of vertical and horizontal curvatures.

Therefore, it is not surprising that visibility studies of the gradual dipping system (Helmers & Rumar, 1976; Schmidt-Clausen, 1979) showed that this approach improved visibility on straight and flat roads for bright and retroreflective targets, but did not improve visibility in most other conditions. In sharp curves and on steep crests the system showed inferior visibility to the conventional dipping system.

6.2.4 Several separate headlight functions

Over the years, many headlighting researchers and designers have proposed that each car should have not only high and low beam but a number of special-function beams that the driver could use depending on the road and traffic situation (e.g., town beam, two-lane rural beam, motorway beam, fog beam).

Already in the sixties it was suggested that the car front should be covered by a series of special lamps for different purposes. Several headlight manufacturers have proposed a similar approach. Each headlamp may consist of up to eight separate units which can be switched on and off separately. By combining some of the units in various ways, the light distribution may be adapted to straight roads, curved roads, built up areas, etc. A disadvantage with this solution is that the headlamp, consisting of several subunits, is likely to become very large. Another disadvantage is that the adaptive function is discrete (stepwise) and not continuous and dynamic.

Schmidt-Clausen (1976) proposed and evaluated a special motorway low beam with an intense, high and square, asymmetric sector on the right-hand side.

6.2.5 ROVELI (Road Vehicle Lighting Integration)

At the beginning of the nineties, a team from Nissan proposed a system in which road lighting adapted to the vehicle lighting (and not vice versa) (Yamada, Honda, & Yamakawa, 1992). In this system an approaching vehicle causes all fixed road-lighting luminaries between 60 and 280 m in front of the vehicle to be turned on. There are some technical problems in setting the present road-lighting light sources to react that quickly.

The concept was tested in a simulator and appeared to be working according to the expectations of the designers. A special effort was made to increase the road lighting intensity between 60 and 160 m in front of the car in order to increase the contrast of the target. This proved successful. The report states that further research is needed and that it will continue.

6.2.6 Active curve lamps

Active curve lamps have been on the market off and on, although to a limited extent. Citroen, for example, had active curve lights in the sixties. Those curve lights were separate lamps, which moved with the movement of the steering wheel.

In the late eighties a team from Koito (Wada et al., 1989) built and tested a steerable forward lighting system. The principle was that a small subreflector in the lamp (which was of the fog-lamp type with a flat, wide, light distribution) could move horizontally in relation with the steering-wheel angle. In left hand curves the subreflector in the left lamp was activated, and vice versa. The system was mainly evaluated subjectively. The results were favorable.

Later, another Koito team (Kobayashi & Hayakawa, 1991) developed another slightly different system with partial beam control and the same main objective—to improve driver visibility in curves. But they also had a secondary objective, which was to use the lamp as an auxiliary lamp to also improve visibility on straight roads. Instead of a subreflector, they used two extra, moveable mirrors in each headlamp. The position of these mirrors was determined by the steering wheel angle and the speed of the car.

The same team (Kobayashi & Hayakawa, 1991) also designed a more general headlamp with the same purposes and the same independent variables. This was based on a moveable lens in a projector lamp. That design offers a more complete control of the beam than the previous one. However it also requires a more complicated processing unit.

Both systems were only evaluated on the basis of the form and character of the light distribution. That evaluation turned out positive both on curved and straight roads.

Honda and Stanley Electric developed a special active headlight system to overcome visibility problems in curves and intersections (Gotoh & Aoki, 1996). This is a system that consists of one fixed and one horizontally turnable headlight. An onboard computer selects the horizontal angle based on three variables: steering-wheel angle, vehicle speed, and position of the direction-indicator control switch. An early version of this system was evaluated by Sivak et al. (1994). For a gentle left hand curve, the results showed a 14 percent increase in visibility distance for the driver, with only a modest increase in discomfort glare for the oncoming drivers. For a gentle right-hand curve, there were only minor changes in both visibility distance and discomfort glare.

In summary, it can be said that the results are promising but not conclusive. It is important to find the right light distribution and the right way of dynamic motion in order to achieve optimal visibility, comfort, and acceptance.

7. Outline of an adaptive direct-illumination system

7.1 Main variables

An adaptive direct-illumination system would be more or less dynamic. Consequently, the light distribution characteristics (such as intensities at various angles) could be changed as a function of the ever changing spatial situation for one car on a road, or the relationship among several cars in a traffic scene. The main variables of interest are:

- Speed of the car(s)
- Vertical and horizontal curvature on the road
- Vertical and horizontal angles with respect to other cars ahead (depending on road width, number of lanes, horizontal and vertical curves, intersections, etc.)
- Distances and directions to the other cars ahead (oncoming, preceding, crossing)
- Intensities from and angles to the front lighting systems of the oncoming cars as seen from the driver's eyes
- Reflection properties of the road surface (diffuse, brightness, specular, etc.)
- Position of the visual targets (distance, horizontal and vertical angle)
- Reflection properties of the visual targets (luminance factor, retroreflective power, angular size, etc.)

7.2 Problems of adaptation

Adaptation to the simplest variables (e.g., number of lanes) could be handled manually by the driver. In theory, ITS systems could obtain or calculate most of the variables, and thereby supply the data necessary to make a fully dynamic low-beam distribution system. So far, however, it is not possible to get information on all the variables mentioned. For instance, the position of a critical stimulus is possible to specify if it happens to be a vehicle, or perhaps a road sign, but it is not possible with present technology to establish if it is an unprotected road user or an animal.

The adaptive problems of the vehicle illumination systems are, however, only part of the whole problem. There are several other difficult problems that remain to be solved before adaptive systems can be introduced. Some of them are specific for the direct illumination systems, but most of them are general and concern direct and indirect illumination systems, as well as illumination systems that adapt to general illumination and atmospheric situation (see Section 4 above).

The most frequently discussed problem for direct illumination systems is to optimize the low beam distribution for each specific situation. Logically, that problem should be the first one to solve before discussing systems that can adapt to actively changing situations. If, however, this project should take on that task, it would never get any further. This problem is of the same type as that of optimizing the low beam system for two oncoming vehicles on a straight, flat road. And that is a task that researchers, manufacturers, and administrators have been working with for about fifty years without coming to an agreement. There is still no international agreement even on that comparatively simple problem. One reason is that there is no low beam design that is superior in all conditions. They all have their advantages and disadvantages.

However, the main reason for the lack of agreement is probably that there are both scientific and commercial arguments for and against each proposal. The true motivation for a position is not always presented. The problem of finding optimal light distributions for each specific situation will, therefore, not be treated here.

7.3 The primary variable: cars or no cars ahead

The main task of the direct illumination system is, of course, to illuminate the road and the road scene in front of the car. The four main areas to illuminate are

- Road surface with its markings and obstacles from very close to the car to as far down the road as possible.
- Road sides with possible obstacles, such as side-post markers and signs, from about 45° to the right and left to as far down the road as possible
- Area of possible overhead road signs from about 60° up to as far down the road as possible
- Areas adjacent to the road with potential targets, such as animals, pedestrians, etc. from about 45° to the right and left to as far down the road as possible

Therefore, the general task of the adaptive light distribution is to avoid the oncoming and preceding cars while illuminating well enough the remaining areas of the traffic scene.

The first input variable for an adaptive system is the presence of oncoming and preceding cars. However, it is less important to know whether there are cars waiting at adjacent intersections, since these stationary cars will have to accept the discomfort of a strong light in order for the moving driver to have acceptable visibility conditions.

If there are one or more oncoming cars or lead cars, the glare levels directed toward those cars will have to be regulated and limited while sufficient road illumination is maintained. This is in essence the task and the major difficulty in development of adaptive vehicle illumination systems.

7.4 No visible vehicles ahead

With no cars ahead, the adaptive function is comparatively simple, and only a limited number of variables need to be taken into consideration.

Our knowledge concerning the minimum light intensities required to achieve acceptable visibility distances is insufficient. One of the main reasons is that we have always been forced to weigh what we would like to have against what is technically and practically possible to achieve, considering the road and vehicle parameters in a dynamic situation. With adaptive vehicle illumination systems we are free to speculate on the illumination necessary at one point, independent of what is required at other points. The illumination values should, in general, be as high as possible, except for two areas:

- Illumination against large retroreflective surfaces, such as large directional sign panels, which may cause glare if they are too much illuminated.
- Illumination very close to the car which may create self glare and unnecessarily increase the adaptation level of the driver, especially if the road surface is bright (e.g., covered by snow).

The following working values are suggested:

- The light intensity straight ahead (HV-point) should not be below 200,000 cd. According to Johansson et al. (1969) and Helmers and Rumar (1975), there is not much visibility benefit in increasing the light intensity beyond that value. However, there might be some comfort benefit with higher intensities.
- The light intensity towards sides of the road about 100 m ahead should not be below 50,000 cd (Alferdinck & Padmos, 1990, Sivak & Flannagan, 1992).
- The light intensities towards the sides of the road 25-50 m in front of the car should exceed 10,000 cd (Alferdinck & Padmos, 1990, Sivak & Flannagan, 1992).
- The light intensity against overhead and road-side signs (on the right hand side of the road) should not be below 1,000 cd (Alferdinck & Padmos, 1990, Sivak & Flannagan, 1992).
- The light intensity towards the zone immediately in front of the vehicle (10-50 m from the car) should be between 5,000 and 20,000 cd depending on the reflectance properties of the road surface (Alferdinck & Padmos, 1990, Sivak & Flannagan, 1992, and Sivak & Flannagan, 1993)

What follows are proposed information inputs for an adaptive system in the order of importance.

(1) Speed of the car

The higher the speed, the more concentrated the horizontal beam pattern. A limit of beam spread should be specified for both the narrowest and the widest beam character (greater than 10°, less than 90°).

(2) Road geometry in general

The better the road geometry (in terms of radius of horizontal and vertical curves), the more narrow the horizontal and vertical beam pattern should be. A horizontal and a vertical limit should be specified for the narrow beam (e.g., horizontally more than 10°, vertically more than 3°).

(Variables 1 and 2, no doubt, covary to a large extent.)

(3) Horizontal and vertical curvature of the road

Any difference between the present course of the car and its position a number of seconds later must be taken into account by the adaptive system. This variable is usually dependent on the road and street geometry. By using time instead of distance as the variable of interest, the criterion is fairly independent of speed. The appropriate number of seconds of interest here may vary from about one to five. In rural areas we often drive up to about 30 m/s while in built up areas we normally drive at or below about 15 m/s.

(4) Position of visual targets

Known stationary visual targets, such as the road itself, road markings, and road signs, should be identified and then receive an extra amount of light at a distance that is dependent on retroreflective power of the material, size of the surface, speed of the car, and atmospheric conditions. A less ambitious goal would be to direct more light in the directions with high probability of containing relevant targets. For example, Damasky (1995) plotted the probability areas for positions of road signs relative to a vehicle on several types of roads. Instead of distance to target, time to target could be used to make the function independent of speed. As was indicated earlier, however, a certain degree of caution must be taken not to create glare from large retroreflective road sign panels (see variable 6 below).

(5) Reflection properties of the road surface

The higher the retroreflection properties of the road surface, the less light should be directed down towards the road surface and the more light should be directed further ahead. The purpose is not to create a glare source and not to unnecessarily increase the adaptation level of the driver.

(6) Reflection properties of the visual targets

The better the reflection properties of a target, the less extra light is needed towards the targets.

It is judged that variables 1 through 3 must be covered by an adaptive system, and that coverage of variable 4 and 5 would be advantageous. Variable 6 is judged to be of less importance and can be ignored by the adaptive system.

A discussion of how quantitative data on these variables could be achieved and used in an adaptive system is carried out below in Section 14.

7.5 Visible oncoming or preceding vehicles

In the previous situation there was really no serious conflict between the variables of interest. Rather, the problem is how to obtain reliable, relevant data and how to carry out the tasks in an intelligent way from optical and technical viewpoints. But with oncoming and lead vehicles, the conflicts become apparent and more difficult to solve. The main problem is how to maintain the illumination towards the targets without glaring other road users. Another way of expressing that conflict is to say that all the requirements of the previous situation (with no visible oncoming or lead vehicles) are still valid, but now they are partly in conflict with a set of new requirements (see below). A conflict between these requirements is normally solved by giving variables 8 through 12 (see below) a certain priority over variables 1 through 3.

Our knowledge about acceptable glare values is even less sufficient than our knowledge of the illumination values discussed above. Recent studies show that the ratio between the illumination and the glare levels is more important for visibility than the absolute glare levels (Helmers et al., 1990; Flannagan et al., 1995). Higher values of both illumination and glare seem to result in increased visibility. This requires that drivers are willing to accept a higher discomfort to gain visibility. That is not always the case. One relevant problem that is often mentioned is the steadily increasing number of older drivers and their increased glare sensitivity.

Furthermore, the glare values should be weighted in relation to the angle between the meeting cars and the distance to the oncoming cars. These conditions together make it very difficult to specify upper glare limits in absolute numbers.

Thus, the recommendation is to keep glare as low as possible, but not to jeopardize the illumination levels. We should not be afraid of glare if higher glare is coupled with improved visibility.

In addition to direct glare, one needs to consider indirect, reflected glare. Studies indicate that on smooth, wet road surfaces, glare caused by specular reflection of the oncoming light distribution may be as high as four times the glare caused by direct glare from oncoming headlights (Wilkenson, 1973). Specular glare is, consequently, in some situations a substantial problem.

The following variables could be entered into the adaptive system on top of the previous ones (variables 1 through 3, and perhaps 4 and 5) in the following order and with the following relative weights:

(7) Distance to the oncoming vehicle(s)

The closer the oncoming vehicle, the less light should be directed toward the oncoming vehicle. This should be for vehicle separations between about 1000 m and 30 m, depending on the angle between the cars and the lateral separation of the cars (see variables 8 and 9 below). This is applicable to one as well as several oncoming vehicles.

(8) Horizontal and vertical road curvature

The smaller the three-dimensional angle between the course of one's own vehicle and the oncoming vehicle, the less light should be directed toward the oncoming vehicle (in order to limit the glare). This variable is dependent on road geometry and is applicable to one or more oncoming vehicles.

(9) Lateral separation between the courses of approaching vehicles

The smaller the lateral separation between the courses, the less light should be directed towards the oncoming vehicles (again to limit the glare).

(10) The intensity of the light from the oncoming vehicle(s) without adaptive illumination system)

The light intensity projected toward the oncoming vehicle should be comparable to the light received from it.

(11) The reflection properties of the road surface

The higher the specular reflection characteristics of the road surface, the less light should be directed toward the road surface between the oncoming cars (in order to reduce specular glare). This is contrary to considerations for variable 5 above. Therefore, variable 11 must have priority over variable 5.

(12) The angle to the preceding vehicle(s)

Glare from rearview mirrors may be reduced two ways: through adaptive lighting systems on the vehicle behind or through variable-reflectance of rearview mirrors. In the situation outlined here with adaptive illumination systems, the light intensities will be stronger than for traditional low beams, and it is therefore probably necessary to combine both methods.

Therefore, the light intensity directed into the rearview mirrors and the rear window of the preceding vehicle(s) should be somewhat reduced. It is important to specify by a three-dimensional angle where in the light distribution the preceding vehicle is. Only in curves and/or depressions is it necessary to consider more than the closest of the preceding vehicles.

(13) The distance to the lead vehicle(s)

The closer the preceding vehicle the less light should be directed in the direction of its rearview mirrors and rear window. Beyond a certain distance, say 400 m, the presence of preceding vehicles could be disregarded. Beyond that distance glare could be regulated by variable-reflectance mirrors alone.

(14) The position of the rearview mirrors (interior and exterior) of the lead vehicle

The higher the position (for instance in a large truck), the more light can be directed in the direction of the road beyond the lead vehicle.

Variables 12, 13, and 14 deal with adaptive illumination systems with the purpose of limiting the glare via the rearview mirrors. As is indicated above, the goal here will be to make a "division of labor" between the illumination adaptive process and the mirror adaptive process to solve this problem in the best possible way. The adaptive vehicle illumination system will solve the initial most intensive problem and the mirror adaptive functioning will control the less intensive part of the problem.

(15) The height of the eyes of the driver of the oncoming car

The higher the driver's eyes, the more light can be directed in the direction of the road beyond the oncoming vehicle.

Variables 7 through 10 should be covered by an adaptive system. Variables 11 through 13 should be covered to some extent, while coverage of variables 14 and 15 do not have the corresponding potential and are also very complicated. Therefore they are of secondary interest here.

Again, a discussion of how it could be possible to obtain quantitative data necessary to achieve the adaptive functions outlined is given below in Section 14.

8. Outline of an adaptive indirect illumination system

No formal scientific evaluation yet exists for any of the four types of indirect systems mentioned in Section 3.2 (side, under-carriage, top, road marking). Side lights have been tried in pilot tests, but not systematically evaluated. Under-carriage lighting has recently appeared in the U.S. The top and road making systems exist more as concepts than as real lights. However, they all seem to have some advantages, without having any real disadvantages. Therefore they will be treated here.

While indirect illumination systems are not intended for built-up areas, the advanced road-marking indication could be useful at intersections in built up areas. Under-carriage illumination might aid unprotected road users, who would be better able to localize oncoming vehicles so equipped.

In the following, however, only the rural situation without street lighting is considered. Also, because the indirect illumination systems are intended for other road users, they are only meaningful if there are other road users in the traffic scene.

8.1 Main variables

The main lighting variables for the indirect illumination systems are the following:

- The illumination against the surfaces intended to be illuminated, or rather the luminance levels created on the road surface or on other relevant surfaces or targets
- The projected area (from the eyes of the other drivers) of these illuminated surfaces
- The glare intensities caused by the lamps and the glare angles in the direction of other road users

The main traffic variables that will influence the adaptive characteristics of the systems seem to be comparatively few:

- The distance to other oncoming, intersecting, or following vehicles
- The reflection properties of the road surface
- Atmospheric conditions
- Angle towards the oncoming or following vehicle (for glare considerations)

The dependent variables, again, are visibility and comfort. For these indirect illumination systems, however, it seems logical to add a third criterion: perceptual interpretation of the traffic scene, including both localization and identification of the other road users and targets.

8.2 Side and under-carriage illumination systems

The side illumination and the under-carriage illumination will be treated together since they have very much the same purpose and the same independent variables.

The first variable for an adaptive system is the presence of other road users. Thereafter, the input into the adaptive system could be in the following order of relative importance:

(1) Presence of other road users

When no other road users are present and visible in the traffic scene, the side illumination and the under-carriage illumination should be turned off.

(2) The distance to other road users

The farther away other road users are, the stronger the illumination. However, a maximum illumination level must be specified.

(3) The reflection properties of the road surface

The higher the specular reflection properties of the road surface, the less effective are these indirect illumination systems. This may lead to two opposite conclusions: to recommend increased illumination in conditions of higher specular reflection (in order to compensate for the lower efficiency), or not to let specular reflection properties of the road influence the indirect illumination level (otherwise there is danger of increasing the risk for detrimental glare effects on road surfaces with highly specular reflection).

(4) Atmospheric condition

The denser the atmospheric condition, the stronger the indirect illumination can be. The side illumination may even change light distribution in the sense that more light may be directed horizontally in order to create a luminous wall, against which the other road users may see obstacles as silhouettes.

(5) Glaring light towards other road users

If for some reason the angles between the road users are such that the light is directed towards another road user, glare would be a problem and would need to be suppressed. However, proper design of the lamps would make this an unlikely event.

Variable 4 is closely related to the variables relevant for illumination systems adaptive to atmospheric conditions (to be discussed in Section 13 below).

A cursory analysis suggests that neither of these two indirect lighting systems have very much to gain from being adaptive. Furthermore, our current knowledge is insufficient to design side and under-carriage lighting that would be adaptive.

8.3 Top lights and advanced road marking lights

These two systems are treated together since they both have the same purpose—to facilitate driver's estimation of the position of other not directly visible vehicles with oncoming or crossing trajectories. But the two functions are very different in terms of their construction.

(1) <u>Presence of other road users in the traffic scene</u>

Even if other road users are present and visible in the traffic scene, the illumination system should not be switched off, since other road users may be present but not yet visible.

(2) <u>Distance to other road users</u>

There is an upper distance limit beyond which the illumination system is not relevant, because it is of no use for the other road users. This distance is likely to depend on many variables. It may be 1 to 2 km (e.g., in overtaking situations) or it may be about 20 m (e.g., in city intersections). There is also a lower limit, beyond which the illumination is of no interest. This occurs when the vehicle itself becomes directly visible. However, this is irrelevant if other road users are also present (see variable 1 above).

(3) <u>Weather and atmospheric conditions</u>

In completely clear and clean air, the top lights are of no use. In very heavy and adverse road conditions such as thick snow or dirt the advanced road markings are of limited interest.

8.4 Concluding comments

Neither of these indirect vehicle road illuminations seems to benefit very much from being adaptive. Therefore they are not treated in the following. However, they have relevance to safety, and further systematic studies and trials should be carried out.

9. Present vehicle lighting systems intended for use in street lighted areas and in daylight

Currently there exist at least two types of vehicle headlights intended for use in areas where the ambient illumination supplies the main part of the light necessary for vision—town (city) beams for street lighted areas and daytime running lights for daylight.

9.1 Town (city) beam

There are two major problems with vehicle headlights in areas with street lighting. One is that the glare from the headlights may mask the often very weak contrasts between target and background. The other is that while vehicle lighting usually produces positive contrasts (bright objects against dark background), street lighting usually produces negative contrasts (dark objects against bright background). Consequently, the two systems may counteract each other and produce worse visibility conditions than either of them separately.

The need to adapt vehicle illumination systems, especially low beams, to the street lighting conditions has long been recognized (Fisher & Hall, 1970; Schreuder, 1974). Several efforts have been made to find optimal light intensities and light distributions for the town beams (Fisher, 1974; Bindels, 1977; Hörberg & Rumar, 1975). The goal has been to find light intensities that are low enough that they do not disturb the contrasts created by street lighting, but which are high enough to make the car itself conspicuous and to make retroreflective signs and markings visible and legible. In general, the proposed intensities in the central part of the light distribution are between 50 and 150 cd.

The British even designed, introduced, and evaluated the so-called dim-dip system for this purpose (Reid, 1979). The dim-dip is a low beam that can be dimmed. By means of a resistor, the voltage to the low beam is reduced when the car enters a street-lighted area. The resistor reduces the intensity of the low beam to about 10 percent of its original value. The dimming may be controlled by the driver or be automatic. When it is done automatically it is controlled by a sensor that is sensitive to the 100 Hz component in the street lighting. The automatic British system is, consequently, adaptive in its real sense, while the others are switched on and off or operated by the driver.

9.2 Daytime running lights (DRLs)

Vehicle front lighting is used not only during night driving. It is also used in a limited (but increasing) number of countries to make vehicles more conspicuous during daylight. In Sweden, Finland, Norway, Denmark, and Hungary, it is compulsory to drive with lights on during daylight. In Canada, Poland, and Austria low beams are not compulsory except for specific cars, areas, or times. Normally, but not always, the light used is the low beam. Often the low beam is slightly reduced in voltage. When the high beam is used it is considerably reduced in voltage. Sometimes special running lights are used. The light distribution requirements for special DRLs differ from country to country, but the maximum intensity in the central part lie between 200 cd and 7000 cd (CIE, 1993).

DRLs are a way to adapt vehicle front lighting to daylight conditions. They are, however, not adaptive in the true sense, since the driver has to handle the switching. In the Nordic countries, in Canada, and with some late-model-year cars in USA, the lights are, however, turned on and off automatically when the engine is started and stopped. For reviews concerning DRLs see CIE (1993), Koornstra (1995), and Elvik (1996).

Contrary to the town beam, the daytime running lights have no illumination purpose. Consequently, they do not really belong to this study, which is limited to vehicle road illumination systems. However, since the lamps used as daytime running lights may very well be illumination devices that adapt to certain conditions, and thereby become presence lights, DRLs are included.

The present vehicle illumination systems are not only static over road and traffic situations, but also over general ambient lighting conditions. There are two main ambient illumination variables that the vehicle illumination systems should be able to adapt to—daylight characteristics and street lighting quality. Because the two types of vehicle lights (town lights and DRLs) differ in many respects (illumination task, glare risk, variable to adapt to, etc.) they are in the following treated separately.

10. Outline of headlights adaptive to street lighting conditions (town or city beams)

The town beam must fulfill two purposes. It should illuminate the parts of the traffic scene that is not illuminated enough by the fixed overhead illumination. It should also mark the vehicle so that it is conspicuous enough to other road users. The light is intended for all roads with street lighting, rural as well as urban.

The main variable is the presence of good quality street lighting. Good quality, here, means street lighting that offers acceptable visibility conditions relative to the road and objects on and along the road. In other words, there is no need for vehicle illumination of these areas. On the other hand, objects above and beside the road (e.g., road signs) might not be adequately illuminated. Also, retroreflective materials and surfaces need illumination from the vehicle to be better visible from the driver's point of view. The light from street lighting does not work on retroreflective surfaces as seen by the driver. Some illumination properties of the town beam are therefore required.

The main independent variables that should influence the lighting characteristics of town beams, are:

- Quality of street lighting (level, uniformity, glare, etc.)
- Reflection properties of the road surface
- Reflection properties of the visual tasks
- Positions of the visual tasks
- Other road users ahead
- Atmospheric condition

Specific sensors and modified ITS systems could supply most of the data necessary to estimate or calculate these variables. A dynamic vehicle illumination system that has the ability to adapt to street lighting conditions would, therefore (at least in theory), be possible. There are, however, conditions for which new mobile sensors are needed. Examples of such conditions are the measurement of reflection properties of the road surface and the quality of the street lighting.

The dependent variables are visibility level, interpretation ability, and comfort.

One general question is whether the quality of street lighting should be classified as good or bad, or whether this should be made a continuous variable. In this discussion, we will presume that the adaptive system is able to classify street lighting in a large number of classes and adapt differently to each of these classes.

The variables to be used to modify the adaptive system could be introduced in the following order and with the following relative weights.

(1) Quality of the street lighting

The better the quality, the less important will be the illuminating function required of the headlights. They can then primarily deal with conspicuity. The quality level of street lighting is based on the luminance level of the road surface, luminance uniformity of the road surface, separate illumination of road signs, and glare from the street lighting luminaries.

(2) Reflectance properties of the road surface

The more specular the reflection is, the more will the town light have to serve illumination. When the specular reflection is high it is also important that the reflected glare from the town beam is controlled.

(3) Atmospheric condition

The more dense the atmosphere, the stronger the town beam will have to be to fulfill its conspicuity function.

(4) Presence of other road users

When other road users are not present and visible, the system can be given optimal light distribution from the visibility point of view (see Section 8.2, variables 1 through 4). When, however, other road users are present and visible, the glare will also have to be taken into consideration and controlled in a way that, in principle, corresponds to the glare control for direct vehicle illumination systems (see Section 7.5, variables 7 through 14).

The three initial variables should be considered by a headlight system that is adaptive to the street lighting conditions. The fourth variable is important. It will, however, cause problems, especially for unprotected road users. It is very difficult to establish the presence of, for example, a pedestrian.

The indirect vehicle illumination systems are of minor benefit in roads with good street lighting. On such roads, they could be turned off (except for advanced road marking illumination).

11. Outline of headlights adaptive to daylight (DRLs)

Because DRLs influence only conspicuity, it is simpler to design an adaptive DRL system than other adaptive systems. For the same reason, adaptive DRLs are of interest only when there are other road users present and visible. When there are no other road users, the light could be turned off. As for town beams this is, however, difficult to register and control.

The independent variables to be addressed in the adaptive process of DRLs are (in order of importance):

- Level of daylight illumination
- Need for wide angle conspicuity
- Atmospheric condition
- Angle of direct sunlight
- Shadow condition
- Vehicle background

(1) Level of daylight illumination

The higher the level, the more intense the light must be. Previous studies indicate that the intensity should vary from about 200 cd at lower levels of daylight illumination to about 7000 cd at the highest levels of daylight illumination (CIE, 1993).

(2) Wide light distribution

In order to improve wide angle conspicuity, in intersections for instance and for pedestrians intending to cross a street, it is necessary to have a wide light distribution (CIE, 1993).

(3) Atmospheric condition

The more dense the atmosphere, the more intense the light must be. While, to our knowledge, no daylight studies in heavy fog exist, it is likely that the intensity required to make an oncoming vehicle visible at a safe distance enough would exceed 10,000 cd. Research is needed to firmly establish this level.

(4) Angle of direct sunlight

The smaller the angle between the sun and the vehicle, as seen from the oncoming or intersecting drivers, the higher the intensity of the light in that direction. Again, firm guidance from experimental studies does not exist.

(5) Shadows

The heavier the shadow in which the vehicle is situated, the less intense the light should be.

(6) Background

The brighter the background against which the vehicle is seen from the oncoming or intersecting drivers, the more intense the light should be.

Adaptive DRLs should include at least the first four of these variables. However, except for the first variable, our knowledge is limited.

12. Present illumination systems for fog

Only the night driving condition is treated here. The properties of the atmospheric conditions with regard to both attention and scattering of light are of interest from a lighting point of view. The first property is important because it affects how much light will reach the target and be reflected back to the eyes of the driver. The second property is important because it affects how strong the reflected veiling light will be for the driver and how strong the silhouette effects will be for oncoming drivers.

Fog is really clouds near the ground. Some areas or regions have very frequent fog conditions, while others may be completely fog free. One specific property of these atmospheric disturbances is that they vary over time as well as over space. They are often not homogeneous vertically and horizontally. Fog layers, for example, often lie some distance above the ground. Dust is often more dense closer to the ground. Smoke varies depending on the wind.

Modern and well equipped vehicles have front fog lights as well as rear fog lights. The rear fog lights are presence lights and are not dealt with here. There are three main characteristics of front fog lights. To begin with, they are normally mounted very low in order to get under the possible fog layers—often about half the height of the headlights. Second, they have a cutoff to prevent light from coming up and being reflected in the field of view of the driver. Third, they often have a very flat and broad light distribution to improve driver orientation laterally on the road (see e.g., Koth et al., 1978).

There are several partly conflicting studies of front fog lights. Some show that fog lights in fog offer considerable gains in visibility. Others find no real advantage in most foggy situations. One problem with most of the existing fog lights, using conventional optical systems, is that the cutoff is not very sharp—often less sharp than the low beam. Modern optical engineering methods such as projector headlamps and free-form reflectors could improve that situation (Treptau et al., 1996).

Another problem is the required aim of front fog lights. It differs from country to country, but is usually equal to or lower than that for low beams. Because the fog lights are mounted so low, the dipping results in very short visibility distances. Still another condition that contributes to short visibility on the right-hand side of the road is that front fog lights do not have the additional light that low beams have on the right hand side. A fourth problem is, therefore, that drivers are tempted to aim their front fog lights too high. This creates glare problems for oncoming drivers.

A fifth problem is that the usage of front fog lamps varies from country to country, and from driver to driver. For example, in the U.S., the usage is regulated on the state level. Sivak et al. (1996) provide information about the usage patterns of fog lamps in a variety of ambient and environmental conditions. In the U.S., drivers seem to use the fog lamps during the night mainly as a supplemental low beam. On the other hand, in Sweden, for example, fog lamp usage is clearly regulated. Fog lamps must not be used together with low beam. In fog, they may be used only by themselves, instead of low beams. The reasons are that the use of fog lamps together with low beams have a high probability of causing either glare to oncoming drivers or too much luminance close in front of the car.

A general problem with the fog lamps seems to be that, in many jurisdictions, the authorities have not made up their minds as to whether the fog light is supposed to work together with the low beam or instead of the low beam. Because the requirements on the two types of light functions are so different, the only logical decision, in my opinion, is to develop a separate fog-light function. Without an agreement and a harmonization of this view there probably will not be very much improvement of the fog lights. That is a pity because fog lights are probably the light function that is least developed and consequently has a considerable development potential.

13. Outline of an adaptive front fog light system

The discussion here is limited to fog lights in night traffic. Since there does not seem to exist any scientific proof of the superior efficacy of the previously dominant yellow color of front fog lights, there are no arguments against using white light for fog lights as well.

Valid arguments, however, exist for lower positioning of the fog lights than headlights. However, in this report I have decided to use the same lamps for fog lights as for all other headlighting functions. This is done partly to simplify the design and the analysis, but also because it is felt that the arguments for special mounting height for fog lights are not stronger than the arguments for the same mounting height and position for all headlights (or adaptive front lights).

The main atmospheric conditions that should influence an adaptive illumination system are:

- transmissivity of the atmosphere (density of fog, haze, snow, rain, smoke, dust, etc.)
- reflectivity of the atmosphere in vehicle illumination systems (whiteness of fog, haze, snow, rain, smoke, dust, etc.)

In addition to these atmospheric variables, the variables that have to do with target visibility and glare towards other road users must also be taken into consideration (see Section 7 variables 1-3, 7-11). Of special interest here are

- Position of the targets
- Distance to oncoming vehicles
- Road geometry

The following variables should be used to control the adaptive process. The order is intended to be the order of importance.

(1) Transmissivity of the atmosphere

The denser the atmosphere, the more intensive the light must be, the higher the aiming of the fog lights may be (up to the horizontal), and the wider the beam should be. If the fog light function is only used in fog, it is suggested that the dipping should never be more than 0.3°.

(2) Reflectivity of the atmosphere

The higher the reflectivity of the atmosphere, the sharper the cutoff should be.

(3) Position of visual targets

Known targets with high retroreflective properties (e.g., road signs and markings) should get an extra amount of light at a distance when the emitted light will both reach the target and be reflected back to the driver.

(4) Distance to oncoming vehicles

When the fog is light and the oncoming vehicle(s) are close, glare against the oncoming driver(s) will have to be limited. The closer the oncoming vehicle, the less the intensity directed against it should be.

(5) Road geometry

When the fog is light, road geometry is a factor. The lower the geometric standard of the road, the wider the light distribution should be.

An adaptive front fog light system should cover at least the first two variables.

One problem is to sense and classify the transmissivity and the reflectivity of the atmosphere. To our knowledge, no such sensors are currently available within ITS systems. Mobile, simple sensors that can carry out such measurements would need to be developed and introduced.

The combination of functions that can adapt to the road, the traffic, the ambient illumination, and also atmospheric conditions might pose new and difficult problems. Furthermore, the vehicle atmosphere adaptive illumination system may change purpose and character with increasing atmosphere density (e.g., from direct to indirect illumination systems).

14. Ideas about how to measure variables of interest in the adaptation process

The ambition of this study is not to suggest technical solutions but to try to structure the problem area. In this section an effort is nonetheless made to give some general ideas about the availability of the variables mentioned as potential inputs into adaptive vehicle illumination systems. Are they available? Can they be made available? Is it possible to quantify them? Do algorithms for adaptive functions seem feasible?

There are a number of technical prerequisites for the suggested solutions. For example, one such prerequisite would be a road data bank with detailed information about all public roads. This information should cover road geometry, width, surface characteristics, signing, marking, horizontal and vertical curvatures, intersections, road lighting quality, etc. Another function that could be introduced is an accurate (with a resolution of less than 5 m) positioning system (GPS). Other suggestions include using transponders on all road users. A transponder is a small, passive, electronic device, which answers when a transmitter asks for it. It may contain information about what category the wearer belongs to (pedestrian, cyclist, car, truck, etc.). It may reveal its position in relation to the asking vehicle.

The following issues are important, but they are outside of the scope of this report:

- How to analyze the information sources suggested
- How to process this information in short enough time that the information is available in real time

14.1 Direct illumination systems

The following are potential data sources for variables listed earlier. Each one of the variables and the possible source is evaluated. Only variables that are considered vital for controlling the adaptive process of various vehicle lighting systems will be included.

(1) Speed of the car

Speed is easy to access with sufficient precision from the car itself. In the future speed will probably be measured against the ground and not from the wheels. This will give a greater precision, necessary for other applications.

(2) Standard of road geometry

This information could be obtained with sufficient precision in two ways: either from accelerometers or other sensors in the car itself, or from the detailed road data bank. In the later case it is necessary to know where the car is. With modern positioning systems (e.g., GPS) this does not pose a problem. Most countries are presently building up road data banks that describe the road network in detail (horizontal and vertical curves, width, pavement, road sign type and position, street lighting quality etc.).

(3) Horizontal and vertical curvature of the road

To our knowledge no such information is currently readily available. However, from the positioning of the car, the course of the car, the speed of the car, and the road data bank it should be possible to estimate the relevant angles with sufficient precision.

(4) Position of visual targets

There are at least four ways to obtain this information. At a basic level of complexity, we could rely on empirical studies of probability areas of target appearance. For example, shoulder-mounted road signs appear with 90 percent probability at 100 m distance within a certain area. Overhead signs appear within another area, etc. Knowing the width of the road from the road data bank and the position of the car from the positioning system, it would be relatively easy to predict the positioning of the road markings. By combining the areas that are relevant at various distances, sectors are defined that should receive a certain illumination distribution. This could be done for most targets. But the precision would not be very high.

A second possibility is to use the information in the road data bank that gives the position of known targets. Together with the position of the car that could be accurate for a limited number of targets. However, targets of unknown position would not be covered by such a system.

A third possibility could be to use some kind of radar to sense the area in front of the vehicle. However, distinguishing between relevant and irrelevant targets can pose large problems.

Finally, there is a fourth possibility, which is superior to the other three. It involves electronically marking the known targets to sense this information and to use it to modify the light distribution accordingly. This is feasible for most critical targets, such as pedestrians, cyclists, parked cars, and road signs, even road markings. But it still does not solve the problem of most unknown targets, such as wild animals. Such electronic markings, in fact, correspond to retroreflective markings in the traditional night traffic scene. However, the transponders would probably be smaller, and less sensitive to degradation. This solution would be a simpler way to make good use of transponders than to have them analyzed and processed by a sensor system, and then to inform the driver about their existence on a display of some kind.

(5) Distance to oncoming vehicles

There are several ways to obtain this information. One possibility is to use distance sensitive sensors (e.g., radar) on one's own vehicle. This probably would be too coarse, and would pose difficulties in distinguishing between different types of objects, directions, and angles. This simple solution can probably be ruled out.

A system used in control of car following distances is video images. That should be feasible system also for adaptive lighting systems. However, accuracy might not be sufficient above about 100 m.

Another possibility is to have two sensors/transmitters on the front of one's own vehicle that are able to pick up and compare the signals from the transponders on oncoming vehicles. This seems to be a solution that is superior to the first one mentioned. But there are still some problems with resolution on long inter-vehicle distances.

A fourth possibility is to use the GPS or other position information, together with information from the road data bank. Those two information sources should allow calculation of distance to oncoming vehicles with sufficient precision. The second and third possibility may be combined and thereby further improved.

A fifth possibility is to have sensors/transmitters in all cars communicating with each other. This is the most advanced and best solution. Each car knows "everything" about itself and together with "everything" from the other cars the information should be complete enough to be able to calculate the distances of interest with sufficient precision.

(6) Road geometry (Angle to the oncoming cars)

This variable is somewhat problematic to get or estimate. However, there seem to be at least four possibilities.

The easiest approach would use the established positions of each car along with the information about the road from the road data bank. This should supply angular position information with acceptable accuracy.

A video technique should be possible also for this application. Another way could be to identify the transponder of the oncoming vehicle and calculate the angle. This method should also be sufficiently accurate for the present purpose here.

A fourth way could be to use an x/y sensitive photocell on the front of one's own vehicle, by means of which the angular position of the oncoming vehicle could be established.

(7) Lateral separation between the courses of the own vehicle and the oncoming vehicle

There are at least two possible ways to obtain this information. Again, one possibility is to use the information concerning the position of each car, together with the information concerning the road from the road data bank. On the basis of these two data sources, it should be possible to calculate the lateral separation of the two courses.

Another possibility is to have transmitters in both cars informing each other about which lane they are traveling in. Together with information from the road data bank, that should give very accurate information about the lateral separation of the two cars.

(8) The illumination intensity from the oncoming vehicle

This variable is different from the others discussed above. It is intended to replace those variables that cannot be obtained for nonequipped cars. Thus, variable is intended to make possible adaptive lighting even with a mixture of cars with and without ITS equipment.

The sensing will have to be carried out with some kind of photocells. However, it is not enough to just sense the illumination from the other car. In order to be able to respond with a corresponding illumination into the eyes of the oncoming driver, we need to know at least the distance and the angle to the oncoming vehicle. The angle is fairly easy to obtain using a direction-sensitive photocell. But the distance sensing will need a special device, perhaps a radar.

(9) The angular position of the lead vehicle

This variable could be handled the same way as the angular position of the oncoming vehicle (see above). A difference is, however, that here the relevant distance is shorter (less than approximately 400 m) than in the previous situation (less than approximately 1000 m). Consequently, reliable measurements would be easier to obtain here.

(10) The distance to the lead vehicle(s)

This variable could be handled the same way as the distance to the oncoming vehicles, and, again, this is probably easier considering the shorter distances of interest.

(11) The reflection properties of the road surface

Again this is a variable that cannot be directly obtained from existing ITS devices. It is, of course, possible to combine the road surface characteristics from the road data bank with the precipitation information from the meteorologists, and in that way estimate the specular reflection properties of the road. However, this method is probably not accurate enough for our purposes. Thus, this variable would probably have to be sensed directly from the car.

A photocell at the front of the car that is able to register the reflected light distribution at a number of points ahead of the car should be able to calculate the specular reflection of the road surface with acceptable accuracy. A more advanced method could be to have a video-photometer register the reflection properties of the road surface ahead.

Another possibility might be to have under the car a lamp at one end and a photocell at the other end and to measure the reflectance properties of the road under the car.

14.2 Systems adapting to ambient lighting

This section covers variables that are important for adapting to street lighting and natural sunlight. The discussion follows the pattern set out in the previous sections.

(1) Quality of the street lighting

Data concerning the quality of street lighting should be available in the road data bank. Based on the position of the car (GPS or other), it should be easy to have this input. If the quality classification is not available, then the relevant parameters will have to be measured directly from the car. This is a somewhat difficult task, which cannot be done with a simple photometer. However by means of a combination of photometers, it should be possible to carry it out with accuracy enough.

Another possibility could be to have a video camera on the car and to analyze the luminance pattern in the picture.

(2) Reflectance properties of the road surface

The quality of the street lighting as it was defined earlier (Section 10) may deteriorate rapidly if the road surface is smooth and there is water on the surface. Luminance level, and primarily luminance uniformity, will both be much lower, and glare from the luminaries (and from the town beam) will be much higher in conditions with high specular reflection. The question is how this should be measured in a way that it could be used to influence the adaptive process.

One approach could involve using information about street lighting quality and road characteristics in the road data bank, combining these data sources with meteorological data concerning precipitation. This would not be very accurate, but probably good enough for most purposes.

Another way would be to measure the situation directly from the car, using the more advanced photometric equipment mentioned under the variable "Quality of street lighting" above.

Finally the analysis of a video picture mentioned above could supply also the information on reflectance properties of the road surface.

(3) Atmospheric conditions

Here the equipment described below in Section 14.4 could be used.

(4) Presence of other road users

The presence of motor vehicles poses only small problems. They could be identified either by their headlights or by their transponders. But the unprotected road users, and especially pedestrians, pose problems. Transponders would still work fine, but there are no headlights that could be used for identification. Some kind of microwave detection (e.g., radar) is probably not accurate enough, since so many irrelevant objects move in the traffic scene, especially in built-up areas.

(5) Level of daylight illumination

A simple photometer directed upwards could probably solve this problem.

14.3 Illumination systems adapting to atmospheric conditions (fog)

The conditions to which this illumination system is intended to adapt are, to our knowledge, not considered by any other existing ITS or other road traffic system. Experience in the aviation field might be of help here.

(1) Transmissivity of the atmosphere

Here we have a new variable in the sense that it is not quantified by any other of the mobile sensing systems. There does not seem to be any simple solution. Fog varies so quickly that any thought of using meteorological data should be abandoned. It appears to be necessary to have two points separated by a known distance to be able to measure transmissivity. The length of the car is probably not long enough. Furthermore the air around the car is very turbulent, which is not ideal for this application.

One possibility could be to use a light source from one of the other cars in the traffic scene. The rear position lamp is then probably the most standardized, least varying light source. If the distance to another car is known (see distance above), then the intensity of its rear position lamp should give a fair estimate of the atmosphere transmissivity. When several cars have been measured the same way, the estimate should be rather accurate. The same method could be used for the atmospheric variable related to town beams (Section 10), and daytime running lights (Section 11).

Here an adaptive system should modify the amount of light directed to targets of relevance and to other road users. The more dense the fog is, the risk of glare for oncoming drivers is lower. In very thick fog, there is no risk of glare. But on the other hand, there are very limited possibilities to illuminate any targets. The direct illumination system will have to work more like an indirect illumination system, creating a bright surface against which targets are seen as silhouettes, and also as a running-light system to make the vehicle sufficiently conspicuous enough.

(2) Reflectivity of the atmosphere

This new variable should be relatively easy to measure. It should be possible to do it from the car, with a fairly simple photometer that remembers the luminance factor straight ahead in clear atmosphere with a certain headlight intensity, and which can compare that with the corresponding luminance factor in a specific fog.

(3) Position of visual targets

See discussion under the same heading in Section 14.1.

15. Combination and integration of different adaptive systems

Because we have decided that it is not really meaningful to make indirect illumination systems adaptive, we have to treat the interactions of four types of adaptive systems. These four systems seem to fit into two major groups, which are fairly homogeneous as to their character:

- Adaptive direct illumination systems including adaptive front fog lights
- Lighting systems adaptive to ambient illumination including atmospheric conditions (DRLs and town beams)

15.1 Integration of road and traffic adaptive direct illumination systems (including adaptive fog lights)

Does any contradiction appear between the way the independent variables are treated, when we try to combine and integrate the various variables relevant to the adaptive functions of direct vehicle illumination systems (including fog lights)?

What we have done thus far is to indicate which levels of illumination we need, in order to obtain safe visibility distances for a number of targets, and target areas, under different road and atmospheric conditions. Then we have stated that when other road users are present in the scene we have to limit the glare toward these road users as much as possible. At the least, we must not exceed certain glare values.

One problem is the relation between the adaptation to fog and the adaptation to a clear atmosphere. One way to solve this problem is to weigh the priorities of these two adaptations depending on the density of the fog.

The primary problem does not seem to be inconsistent needs, but rather optical possibilities to distribute the light from the headlights in such a way that all these requirements can be fulfilled. This problem is, of course, enhanced if there are a number of other road users present in the scene.

A number of limiting values between different areas would have to be specified. How high a glare is acceptable at a given angle? But to make specifications like that, better knowledge is required. An optical system with considerable precision is needed. Not very many sources of variance can be tolerated.

It seems to be possible to add one variable to the next and thereby, successively, solve possible inconsistencies, by stating certain limiting values. However, it has not been the goal of this project to quantify the variables, specify the limiting values, or to carry out such simulations of adaptive performance.

15.2 Integration of vehicle lighting systems adaptive to ambient illumination (including atmospheric conditions)

The adaptation of vehicle direct illumination systems to road and traffic conditions needs to be combined with the adaptation of vehicle front lighting systems to ambient illumination conditions. It is complicated enough to optimize one of these adaptation functions. An integration of the two types of adaptive systems raises the complication level considerably, because the vehicle's adaptive illumination may change purpose and character with changing ambient illumination levels (e.g., from visibility to conspicuity).

Are there any evident contradictory requirements in the combination and integration of lighting systems adaptive to ambient illumination and atmospheric conditions? Based on a relatively superficial analysis, this does not seem to be the case, at least not to any serious degree.

Just as is the case for the direct illumination systems, there are, of course, some opposing needs. Therefore, value limits will have to be given in specific situations. It is, however, very difficult to suggest such limit values without having a well defined specific situation.

15. 3 Integration of both groups of adaptive vehicle illumination systems

There seem to be no major obstacles in combining and integrating the two different groups of adaptive vehicle lighting systems. However, a hierarchy has to be constructed in order to avoid direct conflicts. Presently, we do not have sufficient knowledge to design such a hierarchy.

16. Summary of estimated improvements and losses that can be expected at the introduction of adaptive illumination systems

16.1 Visibility improvement

Visibility improvement is the primary reason for the development of an adaptive vehicle illumination system. Therefore, visibility improvements must be realized.

There seem to be two ways to estimate the visibility improvement. One is to compare the obtained visibility with an ideal value, the daylight condition. The other one is to use visibility conditions with high beams as the basis for an estimation. Of these two, the high-beam situation is much more realistic and is therefore chosen as a basis for an estimation.

In principle, the high-beam visibility conditions without oncoming headlights give an indication of the potential of adaptive direct illumination systems. If all the relevant variables can be specified, and measured with high resolution, and if it is possible to direct light with a corresponding accuracy, then it should be generally possible to reach almost the same visibility as currently exists for high beams with no opposing traffic.

This would mean a visibility improvement of about five times the present visibility of dark obstacles in situations where low beams are opposed by low beams. For dark obstacles (the worst situation) with otherwise good conditions, this translates to a change in visibility distance from about 60 m to about 300 m. For the same situation in more realistic conditions with degraded equipment, the corresponding figures are estimated to be 40 m and 200 m respectively.

In reality, because of difficulties in obtaining accurate values of the independent variables and in distributing the light with high precision, this is not realistic. However, significant progress would be made if visibility distances could be doubled. This would increase the detection distances in difficult situations but good conditions from 60 m to about 120 m. In more realistic situations this would increase from about 40 m to about 80 m.

There is no indication that a decrease of visibility for drivers might appear in any situation as a consequence of the introduction of adaptive illumination systems. However, there is a risk that the visibility conditions for pedestrians and perhaps also for bicyclists will deteriorate. The present viewpoint is that it is more important that the driver can see the pedestrian than it is that the pedestrian is comfortable and can see ahead. Even if this is a topic for argument, it could probably be acceptable for the pedestrian. But it is probably unacceptable for bicyclists. One way to avoid the bicyclist problem would be to have all cyclists equipped with transponders (see Section 14.1 above), and thereby sense where they are and avoid glaring them.

16.2 Road user comfort

If adaptive vehicle illumination systems work well, comfort benefits should be considerable as well. However, if there appears to be unforeseen problems and conflicts in specific situations, we have taken the position to favor visibility over comfort. Therefore, if such situations should appear, it is quite possible that there are some situations in which comfort might be reduced, in order to improve critically short visibility distances. Furthermore, as was indicated earlier, the comfort for pedestrians and perhaps bicyclists, might deteriorate, since that is considered secondary to driver visibility.

16.3 Driver compensatory behavior

The risk homeostasis theory (e.g., Wilde, 1982) postulates that people adapt to the conditions offered in such a way that when active safety improvements are introduced, people change their driving behavior so that safety remains largely unchanged (e.g., by driving faster). One crucial condition for compensatory behavior to appear is feedback. The driver must notice the safety improvements. That is why passive safety measures (e.g., breakaway lighting poles) do not seem to create as much compensatory behavior as active safety measures (e.g., studded tires).

Presently it is generally agreed that compensatory behavior exists, and the question is mainly how large these effects are for a specific measure (OECD, 1990). If adaptive vehicle illumination systems succeed in improving visibility to the extent outlined above, drivers will no doubt notice this. Consequently, this perception will most probably influence driver behavior in a compensatory direction as stated above. The question that must be studied is how much those behavioral changes might affect safety.

One argument against large compensatory effects is that even now, with inadequate front lighting systems, the speeds on roads are almost the same as they are in daylight with very good visibility conditions. Would driving be much faster at night if we had better headlight systems? In order to know the answer to that question we must study the problem.

16.4 Other effects

One effect of advanced adaptive functions, such as the ones described here, will certainly be that the illumination system will be less robust and more sensitive to various sources of disturbance. This means that all measures will have to be taken to avoid this consequence. There are several sources of such disturbances. One is electronic, including both component failures and processing errors. Another one is environmental, including, for example, equipment functioning at extreme temperatures, and dirt or water droplets on headlights and sensor surfaces.

Effective cleaning seems necessary for an adaptive vehicle illumination system. A third cause is mishandling from the operator or from the maintenance staff.

The driver should always be able to override the system. If the driver feels that the system is not working according to expectations, he or she should be able to take command.

In addition to avoiding failures in the first place, it is also important that if the equipment does break down, it does so in a fail-safe way. For example, if the adaptive control of the headlights for some reason breaks down, two requirements should be fulfilled:

- The system should return to the old way of manual operating
- The system must inform the driver of what has happened and what action should be taken.

The adaptive illumination systems must also be able to work in situations where we have various proportions of equipped and unequipped vehicles. The transition period will be long, maybe about ten years, and any system that cannot function well during this period will not be acceptable.

16.5 Probable acceptance

If the functioning of an adaptive system is successful and fully automatic, there is no need to fear that drivers will not accept it. A larger problem is, however, whether they are willing to pay the increased price of complicated systems like the ones described here.

If, on the other hand, the adaptive systems will be sensitive, repeatedly in need of adjustment, showing a high frequency of failure and malfunctioning, then drivers most certainly will not be willing to pay the increased cost.

The unprotected road users might not be totally accepting of the systems. At least not until they realize that it is really built to improve their safety, but not necessarily their comfort.

It is important to mention also that the transition period is an important factor for acceptance.

17. Major potential obstacles to the introduction of adaptive illumination systems

The potential negative aspects of adaptive vehicle illumination systems seem to be: increased costs to buy, maintain, and upgrade the systems; problems with functionality; difficulty in learning to use the systems; threat to privacy; and problems with reliability and maintenance.

17.1 Political

One problem of a political nature is how regulations needed for these new systems will be designed and who will write them. It is probably easier to design adaptive systems if they are built on common principles and technologies. This would require a worldwide harmonization of regulations. Since that is very rare within the automobile industry, a solution for this problem will be difficult to achieve.

Another problem involves liability issues. Who would be responsible if a failure of an adaptive system contributes to an accident? Presently the driver can always be made responsible. But with adaptive automatic or semiautomatic systems, that might not be the case. Industry may be very hesitant to introduce systems that may lead to new legal responsibilities and litigation problems.

Because society also will have to invest in order to make the adaptive vehicle illumination systems work smoothly, this cost variable is politically important. If the compensatory behavior reduces the expected safety improvements, the political interest and willingness to invest money will certainly be reduced. Another reason for hesitation to invest public money is that all the advantages could go to those with equipped cars, while those who have to stick to their old cars see no advantages.

Finally, the threat against privacy is a sensitive political variable. Experience from automatic debiting systems show this convincingly.

17.2 Public

Public acceptance has already been touched upon (see Section 16.2). There are seven major factors involved:

- Handling and operating characteristics (no new driver tasks)
- Reliability (works perfectly every time, in all situations)
- Functionality (does what it is supposed to do and nothing else)
- Cost (to the consumer)
- Responsibility (who is to blame if something happens?)

- Threat to privacy (who was where when?)
- Transition time and problems (before all vehicles are equipped)

A very important problem that always comes up when we are designing technical systems to replace human decisions is that we have to set values on the safe side; we have to adapt the systems to the worst drivers. Consequently, more than half of the driver population perceive the system to be too conservative. Adaptive lighting systems will encounter these problems. Different individuals are not equally sensitive to glare, need more light to see than other drivers, etc. This problem is one of the major problems for ITS. It will also be one of the major problems for adaptive vehicle illumination systems. Somehow it must be possible to tailor-make the limiting values for illumination and glare, to teach the system which values a specific driver prefers.

17.3 Economic

There are two cost factors:

- One for society (What are the infrastructure costs? Are the systems cost effective for society?)
- One for the user (What are the vehicle costs? Does the driver get what he wants—better visibility and greater comfort?)

No effort has been made here to estimate the actual costs of a complete adaptive vehicle headlighting system. The costs will have to be weighed against the expected benefits in terms of improved safety. User reaction cannot be tested without having prototypes available.

17.4 Technical

The technical problems have been touched upon several times. The optical and information technology problems that have to be solved to make a complete adaptive system are substantial. One possibility is to use a stepwise approach, from present design to the most advanced design.

The efforts to limit glare from present low beams have thus far been one dimensional. That is to say, the light distribution has been dipped or tilted to minimize glare for oncoming drivers. What is proposed here is a two-dimensional modification of the light distribution. The ambition is to make "holes" in the light distribution, where the oncoming or preceding vehicles are situated. We are not talking about black holes, but small areas with considerably reduced light intensities. Not only are these holes small with fairly sharp gradients, they are also dynamic, moving with the other vehicles. This poses new, and considerable, optical and technical problems.

One open but important question is how many "holes" are necessary in normal traffic situations. In slight left curves and on hill crests, for instance, one dark spot for oncoming cars should be enough because most cars are projected within a very limited space angle. On the other hand, in right-hand curves and depressions there must be several dark spots, or an oblong dark area. It is probably not necessary to have more than a few dark dynamic antiglaring areas in an adaptive vehicle illumination system. That should be technically possible to achieve.

18. Ideas about time horizons for various adaptive illumination systems

It is always difficult to predict what will happen in the future. Not knowing what the various adaptive systems will really look like, what they can do, how much they will cost, etc., does not make it easier.

18.1 Within 10 years

One semiautomatic (but not adaptive) system, expected to become more common within the next ten years, is daytime running lights in their most simple design. That means that the lights are turned on when the motor is started and switched off when the motor is stopped. This is a solution that already exists in many countries. It is therefore very simple to introduce.

Another adaptive system could involve fog lamps. One reason for a possible quick introduction could be that the adaptive functioning of these lamps is independent of the introduction of ITS systems. Furthermore, the sensors and the processing parts of the system are not too complicated. Also, the present fog lighting system is, as indicated in Section 12, inadequate. Drivers would really like to have something better. Demand should be there and, consequently, a commercial interest.

The parts of the direct vehicle illumination system that could be introduced during the next ten years appear to be the following:

- Speed sensitive light distribution
- Light distribution adapting to driving in curves and turning round corners
- Light distribution sensitive to distance to preceding vehicles
- Light distribution adapting to high probability target areas
- Light distribution adapting to the reflectance properties of the road surface
- Illumination intensity adapting to the illumination of the oncoming car

These six adaptive functions can be made rather simple, but still effective, in their basic versions. Furthermore, these functions will probably be well received (easy to sell), because they are presently not very well covered by the traditional vehicle illumination systems.

18.2 Within 20 years

Within this time horizon many of the ITS functions intended for other traffic applications should be implemented. This could enable a number of further adaptive vehicle illumination systems that are dependent on the presence of substantial amounts of new equipment in vehicles. This group is likely to include illumination systems adaptive to the following features:

- Road geometry
- Areas where the car will be in a few seconds
- Actual positions of the primary visual targets
- Distance to oncoming vehicles
- Angular position of oncoming and lead vehicles
- Lateral separation of vehicle trajectories.

For the other adaptive vehicle lighting systems, the following functions could be introduced within the next twenty years:

- Adaptive town light
- Adaptive daytime running light

18.3 Beyond 20 years

What will happen after twenty years will probably be a successive improvement of the adaptive vehicle illumination systems. They will have to perform very well because by then we will probably have a number of very competitive solutions, such as polarized headlights, and ultraviolet headlights and street lights. Even nonlighting enhancements of driver vision in night traffic will probably be available at that time (e.g., radar, infrared systems).

19. Conclusions

Available vehicle front lighting systems fulfill five functions:

- Direct illumination systems
- Indirect illumination systems
- Illumination systems for adverse weather (mainly fog)
- Illumination systems for street lighting conditions (town beams)
- Headlighting systems for daylight conditions (daytime running lights)

Driver visibility and comfort would greatly benefit if all of these systems, except the indirect illuminating systems, could be made adaptive and designed into a unified system.

Only a limited number of published studies have been found in the literature that approach the problem of adapting the vehicle illumination systems to the changing road, traffic, vehicle, weather, and ambient lighting circumstances.

For each road, vehicle, traffic, illumination, and environmental situation that the vehicle illumination systems should be able to adapt to, a number of variables were specified that must be measured and known. How these measurements could be achieved was also discussed. The following is a summary of the conditions and of the relevant variables.

(1) Angular spread (width and height) of light distribution

- Road geometry standard
- Speed of the car

(2) Light towards target areas

- Areas with high probability targets (e.g., pedestrians)
- Horizontal and vertical curvature of the road
- Position of known targets (e.g., road signs)
- Position of unexpected targets (e.g., pedestrians)

(3) Limitation of glare

- Position of and distance to oncoming vehicles
- Lateral separation of oncoming trajectories
- Position of and distance to preceding vehicles
- Reflection characteristics of road surface
- Illumination intensity of oncoming vehicles

(4) Adaptation to street lighting

- Street lighting quality
- Reflection properties of the road surface
- Density of the atmosphere

(5) Adaptation to fog conditions

- Transmissivity of the fog
- Reflectivity of the fog
- Position of the targets

(6) Adaptation to daylight conditions

- Level of daylight illumination
- A wide light distribution to improve wide angle conspicuity
- Atmospheric condition
- Angle of direct sunlight

There do not seem to be any insurmountable obstacles to designing a unified adaptive vehicle illumination system. There are, however, substantial optical and technical problems that must be solved before such a system can be realized. This will take several decades, and it would be advantageous if the system could be made in such a way that it could be gradually improved. One way of creating such a first step could be to base the initial adaptive process on multicompartment headlights and not on dynamically changing headlights. The adaptation of the front lighting to the situation could then be carried out by lighting a combination of the compartments in such a way that a fairly good adaptation is achieved. That adaptation would then be discrete and not continuous. It would be limited to a number of preselected light distributions and would not be freely changeable. Such a multicompartment headlight is certainly easier to construct and build than an advanced, dynamically changing headlight.

If an advanced adaptive vehicle illuminating system such as the one outlined earlier in this report can be made, it is estimated that driver visibility levels in the most difficult and dangerous situations will be roughly doubled. That is a goal well worth working toward, both from a safety and a comfort point of view. However, before it can be concluded to what extent road safety during night traffic will increase as a result of the expected visibility increase, it is necessary to study how drivers will adapt their behavior to the increased visibility conditions.

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